

**Systems for Reuse, Repurposing and Upcycling
of Existing Building Components**

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Declaration

I, Colin Rose, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

The construction industry uses natural resources intensively, and causes significant carbon emissions in processing resources to supply useful materials and components. Demolition generates considerable physical waste, accompanied by wastage of the impacts embodied in existing building components. This project explores the failure to capitalise on these embodied impacts, and adopts a mixed methods approach to develop interventions and identify potential mechanisms for change.

The main contributions of the thesis are:

Firstly, an exploration of the notion of 'component management'. This challenges the assumption that components removed from the building stock must either be: a) directly reused, which can often be impractical, and is rarely given due attention, or b) sent to waste management, which wastes embodied impacts. Instead, the role and implementation of repurposing and upcycling are described, alongside a procedure for comprehensively checking the practicality of direct reuse;

Secondly, the development of an urban-level 'triage': a process to separate out components for reuse, repurposing and upcycling, from those for which downcycling or energy recovery are the best option. Key to the triage is an information system; the thesis reviews current means of understanding existing buildings as material banks and presents a new approach to gathering this information;

Thirdly, a proposal for an innovative manufacturing enterprise using secondary timber in a new product: cross-laminated secondary timber. This provides an exemplar case study of the potential for industrial-scale upcycling. A proof of concept study is presented, with a preliminary examination of technical feasibility and leading the way for additional investigation of socio-economic and environmental sustainability, and, ideally, future pilot- and commercial-scale implementation.

The implications of this product case study are synthesised with the other parts of the thesis in a discussion of areas for future research, policy and practical action to evolve a more nuanced and sustainable management of existing building components.

Impact statement

The impacts of the research range from immediate benefits in the local context of the project, through, for instance, facilitating the exchange of materials discarded from construction sites to new businesses and community projects in the London Borough of Tower Hamlets, to incremental take-up of ideas that could have an impact on an international level. Investigations into the urban-level management of existing building components have led to policy recommendations that could be adopted by cities in many contexts. These have been disseminated through articles published in international peer-reviewed journals and at conferences and academic workshops around Europe.

Co-authors of journal papers and conference contributions have included academics, members of the industrial sponsor organisations and a practising engineer. Collaboration with another practising engineer led to the dissemination of a product innovation, cross-laminated secondary timber (CLST), through public engagement at the Victoria & Albert Museum in London. The collaborative approach taken in the project has involved supervision of six Master's students' dissertations relating to CLST. A further Master's student produced a video based on this project's initial findings, and intended to raise awareness of construction waste, which has been viewed more than 5,500 times on YouTube.

Development of the concept of CLST has included a commercial pilot project that was carried out collaboratively with an architectural firm, a timber reclamation contractor, a reclaimed timber stockist and a new reuse enterprise. The physical outcomes of the pilot are in use in a co-working space. The non-physical outcomes include forming new connections in a reuse network, generating work for local carpenters and generating workshop rental income for the reuse enterprise.

Publications arising from the research have sought to open new avenues for further thought by other researchers and identify specific areas of further research. The presentation of the idea of CLST has attempted to draw attention to a hitherto unexamined use of secondary timber and indicate the steps that will need to be taken to move the concept towards full-size pilot production and commercial implementation. Timber is a ubiquitous building material and, with incremental progress towards proving feasibility, plants producing CLST could come to serve regions in many parts of the world. In the long-term, this could lead to great environmental benefits (savings in embodied carbon emissions; avoidance of waste disposal), social benefits (employment in reclamation and manufacturing close to urban areas) and economic benefits (extracting greater value from discarded materials).

Given that the Doctorate of Engineering is intended to be applied in an industrial context and to have impact both within and outside of academia, more detail of the impacts of the project are provided in the main body of the thesis.

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List of abbreviations

ASBP	Alliance for Sustainable Building Products
BAMB	Buildings As Material Banks
BIM	building information modelling
BRE	the former Buildings Research Establishment
C&D	construction and demolition
CAWS	Common Arrangement of Work Sections
CIB	International Council for Research and Innovation in Building and Construction
CLT	cross-laminated timber
CLPT	cross-laminated primary timber
CLST	cross-laminated secondary timber
CRWP	Construction Resources and Waste Roadmap
CSE	Chrisp Street Exchange
CWS	City Wood Services
Defra	Department for Environment, Food & Rural Affairs
DfD	design for deconstruction
DOL	duration of loading
E-BAMB	existing buildings as material banks
EPD	environmental product declarations
EWC	European Waste Catalogue
FEM	finite element modelling
GHG	greenhouse gas
GIS	geographical information system
GLA	Greater London Authority
LCA	life cycle assessment
LLDC	London Legacy Development Corporation
LVDT	linear variable displacement transducer
LWARB	London Waste and Recycling Board
MJBT	Mechanically Jointed Beams Theory
MOE	Modulus of elasticity
MOR	Modulus of rupture
PH	Poplar HARCA
PRHZ	Poplar Riverside Housing Zone
RBL	Remakery Brixton Limited
RFID	radio frequency identification
RIBA	Royal Institute of British Architects
RMM	reused material marketplace
RSA	The Royal Society for the Encouragement of Arts, Manufactures and Commerce
SWMP	Site Waste Management Plan
THH	Tower Hamlets Homes
WFD	Waste Framework Directive
WRA	Wood Recyclers Association
WRAP	Waste & Resources Action Programme
WTS	waste transfer station

Preface

“Dirt is only matter in the wrong place.” Lord Palmerston, quoted in *Punch*, 1858: 47.

“We glibly dismiss waste as rubbish. It is not, but [...] we have been too indolent to occupy our minds in the elaboration of further possible applications [...] We have failed to appreciate that what may be of no immediate value to ourselves may, indeed can, with judicious and scientific handling be persuaded to serve in the capacity of indispensable raw material to other ranges of endeavour. It may even go so far as to supply the wherewithal for the creation of new industries, widening the possible fields of employment, and contribute pronouncedly towards the wealth of the nation.” Talbot, 1920: 11.

“[We have] come to identify the termination of one use with the termination of all usefulness.” Pawley, 1975: 11.

“It is not so much by the things that each day are manufactured, sold, bought that you can measure Leonia’s opulence, but rather by the things that each day are thrown out to make way for the new. [...] As the city is renewed each day, it preserves all of itself in its only definitive form: yesterday’s sweepings piled up on the sweepings of the day before yesterday and of all its days and years and decades.” Calvino, 1997: 114.

Lord Palmerston was debating London’s ‘Year of the Great Stink’ when he referred to human waste as ‘matter in the wrong place’ (Fardon, 2013). Of course London’s sewage was of value; it just needed to be in the countryside, used as fertiliser, rather than in the Thames. Mary Douglas made the aphorism famous in her 1966 book, *Purity and Danger* (2002: 44), using it to describe ‘dirt’ as matter that contravenes our desire for order. There is no reason to think that matter discarded by one party would not be useful to another; it is simply convenient to categorise such matter as ‘waste’ and be rid of it, like the daily purge of the streets of Leonia, in one of Italo Calvino’s portraits of a city. As Frederick Talbot recognised almost one hundred years ago, this improvidence could be overcome by seeking out the places and applications in which matter is not waste; in which it can continue to serve our needs (1920: 11, 298). We still struggle with this challenge. Humans’ aversion to waste, and the low cost of many materials, makes the pursuit of secondary uses look disagreeable, unprofitable and complex.

Carrying out this research project has, nevertheless, led me to the conclusion that reuse of existing building components is possible to a much greater extent than is currently seen. To achieve that end, change is needed on a number of fronts. Direct reuse of components will only ever play a minor role. There is much greater scope for secondary use, and multiple uses, when repurposing and upcycling are brought into the equation. This thesis explains the process of reaching those conclusions.

1 INTRODUCTION

1.1 The problem with the construction industry's use of materials

1.1.1 The construction industry and the fundamental processes of construction

Humans' accumulation of manufactured goods in cities is vast. By weight, the great majority of this accumulation is in the fabric of the built environment (Kibert et al., 2000). The growth of urban centres brings together materials from all over the world to create buildings and infrastructure that frame and structure life. This process of turning natural resources into manufactured goods is carried out by the construction industry (understood to mean not only contractors, but also supply chains, sponsors of construction, and all the built environment professions acting together to perform construction: Smith et al., 2002). Society enjoys the benefits of this process: materials are combined and configured as building components, intelligently brought together to create the entranceways, courtyards, bedrooms and auditoria of a city.

The ongoing role of the construction industry is to maintain the existing building stock, to make additions to it in the form of new construction and refurbishment, and to make subtractions from it in the form of demolition and soft strip. The way it presently does so can be seen as an open system (Boulding, 1966): the additions come largely from the wider system of the planet's natural resources, and its waste goes largely into other segments of the anthroposphere, in the form of open loop recycling, or into the planet's natural sinks, through incineration and landfill. Given that the planet is a closed material system, these processes cannot go on forever.

1.1.2 Global impacts of flows of construction materials

The global construction industry uses around 23 Gtpa of non-fuel raw materials (Haas et al., 2015). Extraction of these resources causes environmental damage, loss of habitat and biodiversity, and changes in land use patterns (Tukker and Jansen, 2006). Processing and transporting those resources to supply useful building materials depletes reserves of non-renewable energy, and, in the UK, represents 8% of total greenhouse gas emissions (BIS, 2010; Steele et al., 2015). At end-of-life, a large proportion of these resources become waste, with additional environmental impacts (Figure 1). The waste resulting from removals from the stock causes further emissions through the need for transportation and processing (Chong and Hermreck, 2010), and recycling, incineration with or without energy recovery and landfill can all be the cause of pollution of land, water and air (Haas et al., 2015). As populations continue to densify, and as we continue to dispose of waste to the ground, the physical space available for landfill comes under more pressure; that is, we exhaust the natural sink of land (Power, 2010).

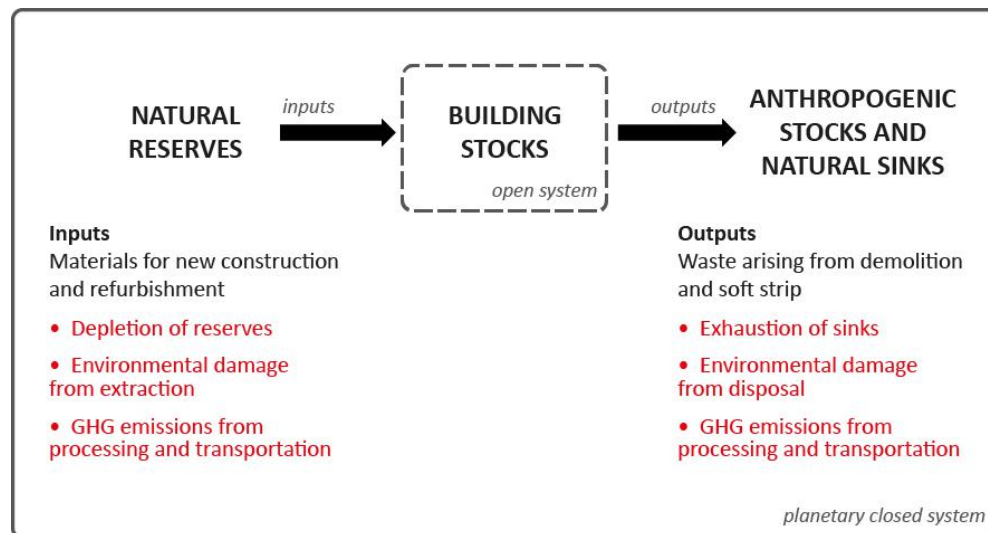


Figure 1: Simplified construction material flows and stocks, and the broad categories of their global environmental impacts shown in red. No impacts are noted for building stocks, as the material changes of repair and upgrade are captured under the flows in and out. The operational greenhouse gas (GHG) emissions of the existing building stock are considered outside the present scope.

Construction activities are responsible for 9 Gtpa of waste globally (Haas et al., 2015), and one-third of total waste generation across EU countries (Eurostat, 2011). The European Commission Waste Framework Directive (WFD; European Commission, 2018, 2008) embeds into law the waste hierarchy's preferential order for waste management: after prevention, direct reuse of a product, then recycling (reprocessing into new products), recovery (such as generating energy through combustion), and, lastly, disposal. Member States are required to achieve a 70% material recovery rate by 2020 for all construction and demolition (C&D) waste except natural soil and stone (primarily arising from excavation, and considered outside the scope of this project) and hazardous waste (European Commission 2008, Article 11; discussed further in section 2.3.1). In the UK, this target has been met: the statutory requirement for Site Waste Management Plans (SWMPs; repealed in December 2013), along with a voluntary initiative led by WRAP, Halving Waste to Landfill (BRE and WRAP, 2012; WRAP, 2007), the Aggregates Levy, and the gradual escalation of the Landfill Tax, have all been effective levers in increasing the material recovery rate (Hobbs, 2011). Around the turn of the millennium, 45% of all C&D waste was recycled (Symonds Group Ltd, 1999); by 2014, the figure had risen to 90% (Defra, 2016). BRE's SMARTWaste data (BRE, 2013), derived from thousands of individually reported projects, indicated a recycling rate of 91% in 2012. However, national and EU legislation does not set separate targets for reuse and recycling, and the main route for waste streams diverted from landfill has been recycling into lower value products – downcycling (McDonough and Braungart, 2002) – often in an open loop (Adams et al., 2017).

There is a danger in assuming that the impact of construction waste has been successfully mitigated as recycling rates rise above 90%. A first problem is that these data are based on whether waste is sent to recycling companies rather than whether it is actually incorporated in new products. Secondly, the impacts of transportation and recycling processes can be

considerable. Thirdly, recycling processes can be highly wasteful. The global image of recycling – the familiar triangle of arrows – conjures an idea of continuous cycles, yet open-loop recycling is better described as delayed disposal (Anderson, 2011) or a cascade (Sirkin and ten Houten, 1994). When, for instance, timber joists are chipped for particleboard, this open-loop recycling still requires trees to be felled, milled, and produced when we want new joists. The recycled wood chip has a lower economic value than the joist from which it came. It also has reduced ‘performance’, considered as its ability to perform a duty (that would otherwise be performed by a material it displaces) over a period of time. A chipped joist only displaces new wood chip (e.g., from forest thinnings), a material with low impacts. In products like particleboard or animal bedding, it can perform a duty for a limited period of time, and will be buried or incinerated relatively soon. A joist retained in its existing form may be able to displace new, kiln-dried sawn wood, and perform the duty of supporting a floor for many decades.

Performance also drops in the case of end-of-life concrete. Recycled aggregate from concrete displaces primary aggregate – a material with low value and impacts compared with concrete. The lower duty performed as aggregate represents a loss of between 70 and 185 kg embodied CO₂/tonne of concrete (Mineral Products Association, 2016). Even recycling of metals entails a loss of performance. Secondary aluminium is contaminated with alloying materials, reducing its performance and value (Nakajima et al. 2010). Properties of products from refining steel scrap do not match those of steel obtained from primary production, so secondary steel is used for reinforcing bar and sections, but not for higher grade and applications like plate and sheet, which have greater impacts (Allwood, 2014).

Schut et al. (2015) report that, in the Netherlands, only 3–4% of material used in the construction of buildings is from a secondary source, despite 95% of C&D waste being recycled. A large proportion of this recyclate becomes fill in road construction. The environmental impacts of waste generation are thus reduced. However, the failure to retain materials as high-performance building components means that the industry’s enormous resource extraction, with all its associated impacts, continues more or less unabated. The requirements of the Climate Change Act (HM Government, 2008a) mean that low carbon solutions will be needed in every part of the economy, and as buildings’ operational emissions are reduced in line with current legislation, the proportion of whole life carbon embodied in construction materials will grow and come to the fore (Giesekam et al., 2016; Lane, 2007; Papakosta and Sturgis, 2017). Current systems of waste management do not satisfactorily support mitigation of the construction industry’s environmental impacts.

Finally it should be noted that across the system there is global inequity: the environmental damage caused by resource extraction and the hazards of waste handling and toxicity are felt more keenly by poorer nations, while the quantity and quality of building stock is enjoyed more by richer nations (Vásquez et al., 2016; Wiedmann et al., 2015). In ecological sciences there is a consensus (Jones et al., 2010) that to respect ecological limits, ‘a tenfold reduction in resource consumption in the industrialised countries is a necessary long-term target if adequate

resources are to be released for the needs of developing countries' (UNEP, 2000). While a tenfold reduction is almost impossible to imagine, and work by Allwood et al. (2011) indicates that absolute mineral shortages are unlikely to be the drivers of change, there is nevertheless an ethical responsibility to improve upon use of material resources.

1.1.3 Risks and resilience in the construction industry connected to its resource use

Discussing the fundamental processes of construction in terms of material 'performance' draws attention not only to its negative impacts on the environment, but also to the positive impacts of its performance-creating activities. An effective construction industry is an essential part of society. This implies a need for industry resilience in changing global and local contexts. The negative global impacts discussed above have corollary risks specific to the continued effectiveness of the construction industry, as set out in Table 1. The suggested means of building industry resilience are intended to mitigate these risks by building the capacity for alternative processes and practices.

Table 1: Global impacts and specific risks to construction industry effectiveness

Global impacts of resource use in construction industry	Specific risks to construction industry	Means of building industry resilience
Carbon emissions	Future legislation enforcing lesser embodied carbon emissions makes current construction methods untenable	Low embodied carbon alternative materials
Resource depletion	Price volatility and ultimately resource scarcity; coupled in the UK with trade deficit and reliance on material imports	Local renewable materials; recirculation of existing materials
Environmental damage	Future environmental protection measures, e.g., designated natural reserves, that reduce supply and increase cost of land and primary resources	Alternatives to damaging extraction of primary resources
Waste generation	Rising costs of waste disposal and the export of waste	Alternatives to disposal

1.2 Responses to the stated problem

1.2.1 Areas of focus to address construction industry impacts

To address the global impacts of construction shown in Figure 1 and Table 1, attention can be focused on three areas: (1) design of new additions to stock, (2) management of existing building stocks, and (3) management of existing building components removed from stock (Figure 2). A review of these areas follows, providing a demarcation of the scope of this study and a rationale for its focus on the third.

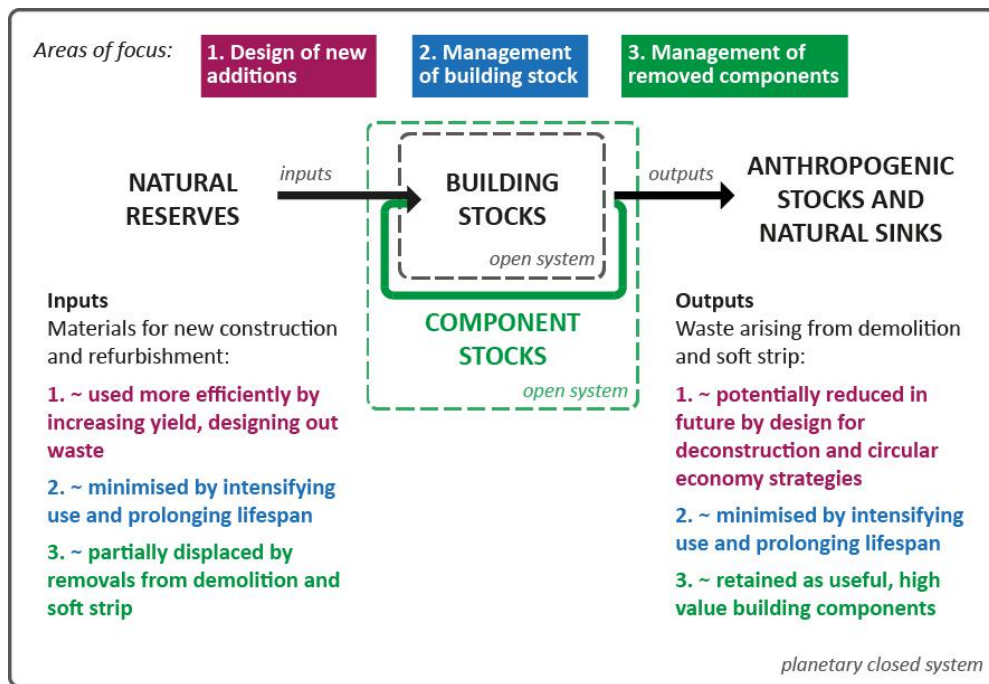


Figure 2: Three areas of focus in addressing waste and material efficiency in construction: (1) design of new additions to stock, (2) management of existing building stocks, and (3) management of building components removed from stock. The focus of the present research is area (3). Improvements to (3) can improve additions to stock (green arrow), but (1) does not rely on the use of secondary components and is described as an independent area of intervention.

1.2.2 Design of new additions to building stocks

Efficiency measures to reduce current resource inputs

Ways of reducing resource extraction and process waste by the design of additions to stock include the following: (a) in production, increasing the yield of useful materials from extracted resources (Allwood, 2014); and (b) in building design and construction, adopting various measures to reduce material inputs or ‘design out waste’ (WRAP, 2010), such as lightweighting to reduce the quantity of material needed to perform the required duty, using off-site prefabrication, just-in-time delivery, and protection of goods on site (Defra, 2007a). These practical measures have been thoroughly covered in the literature (Ferguson, 1995; Guthrie and Mallett, 1995; Osmani, 2012); more recently, there has been a focus on waste minimisation through the use of building information modelling (BIM), inter alia, to coordinate and validate design ahead of construction (Liu et al., 2015; Won et al., 2015; WRAP, 2013).

Reducing future resource inputs and waste outputs: circular economy

Reduction of *future* material inputs and waste outputs is an important aspect of the design of new additions to stock. Approaches in this mould have recently become associated with the idea of a circular economy. This encompasses a range of strategies (Carra and Magdani, 2017; Ellen MacArthur Foundation, 2016; Lacy and Rutqvist, 2015) that aim to overcome the

prevailing linear model of 'take-make-dispose' and which take control of the end-of-life scenario by encouraging greater consideration of the whole life cycle at design stage. Athelstan Spilhaus argued, presciently, that the separation of production and waste management represents a fundamental flaw:

Industry must be encouraged to do the other half of its job, to close the loop back from the user to the factory. If industry itself takes on the job to close this loop, hopefully, with subsidies and assistance from government, then the original design of articles would facilitate their return and remaking. (Spilhaus, 1971)

Until this responsibility is placed on industry, he believed, 'designs for reuse will not easily come about'. Extended producer responsibility covers only a fraction of products, and studies continue to draw attention to the need for closer links between designers and the waste management industry (Allwood et al., 2011; RSA, 2016). Spilhaus also discussed what is now known as servitisation:

One consequence of recycling and reuse is that we will own nothing except works of *art*. We must get used to the idea that we are no longer consumers and there is no longer ownership. We must replace usership for ownership. (Spilhaus, 1971; italics in original)

Circular economy thinking builds on these ideas and many other schools of thought, such as performance economy, cradle-to-cradle, industrial ecology, industrial symbiosis, biomimicry, permaculture and natural capitalism (Ghisellini et al., 2014; Lewandowski, 2016; Prins et al., 2015). Circularity in relation to the built environment (Adams et al., 2017; Debacker and Manshoven, 2016; Ghisellini et al., 2017; Glass et al., 2017; Pomponi and Moncaster, 2017, 2016; Zimmann et al., 2016) harnesses principles from the established field of design for deconstruction (DfD; e.g., Addis and Schouten, 2004; Guy et al., 2002; Morgan and Stevenson, 2005).

Design for deconstruction and buildings as material banks

Designing with disassembly in mind was already common currency in the field of product design in the 1990s. Crowther (1999, 2000) proposed that principles from design for disassembly could be applied to construction, to avoid the loss of embedded energy that he observed in demolition. The International Council for Research and Innovation in Building Construction (CIB) drew together a deconstruction task group in 1999, and held a series of conferences with associated publications (Kibert and Chini, 2000; Chini et al., 2001, 2002, 2003), culminating in an extensive report on the state of deconstruction in ten countries (Chini et al., 2005). Crowther (in Chini et al., 2002) was able to say that 'a developed knowledge base for design for disassembly does not yet exist', but guides aimed at designers and clients soon began to emerge (Addis & Schouten, 2004). Morgan and Stevenson (2005) comprehensively set out principles such as adaptability and anticipation of change, component modularity, reversible and accessible connections, and 'shearing layers' to allow separation of elements of different expected lifespans, based on the ideas of Brand (1994). In parallel, related work on

'industrialised, flexible and demountable' building systems was developing (e.g., Jaillon and Poon, 2014; Richard, 2006; Zeegers et al., 2001) with reference back to Habraken's (1972) principle of separating structure from fit-out in the design and construction of residential buildings (Durmišević, 2016), originally conceived to encourage the inhabitant's participation in the design process.

Alongside designing-in the physical ability to deconstruct buildings and building products, circular economy thinking pursues a change of perception, in which buildings are seen as 'material banks' (Debacker and Manshoven, 2016; Durmišević, 2015). Accounts of the materials deposited within them are to be actively managed through material passports, Internet of Things devices, and BIM (Ellen MacArthur Foundation, 2016; Heiskanen, 2017; Luscuere, 2017; Mulhall et al., 2017; Ness et al., 2015). A material passport would travel with a product through time and could provide information on its origin, composition and potential for maintenance, reuse and remanufacturing (Ellen MacArthur Foundation, 2016). It is hoped that BIM will facilitate the collection and storage of these data over the lifespan of the building; although there may be challenges in storing data in such a way that they remain useable in fifty or a hundred years (Schut et al., 2015).

Building and product lifespan in relation to circular business models and design

While circular economy thinking outside of the built environment sector focuses largely at the level of individual products, buildings are compositions of numerous products with different lifespans, which may be altered in a number of ways during the building lifespan, from routine maintenance to structural adaptation. These factors mean that buildings are complex entities, and represent a different challenge to that of individual products (Pomponi and Moncaster, 2016). Circular economy models for the built environment are yet to reach widespread application beyond specific components that are easily removed and need frequent replacement, such as lighting (LWARB, 2015) and carpet tiles (Morgan and Stevenson, 2005). Such ongoing contractual arrangements between building owner and manufacturer have great benefits in forcing engagement with future end-of-life. For short-lived product groups, it is relatively simple for the manufacturer to make the business case for retaining ownership of valuable resources, and taking them back for remanufacture at end-of-life. The suitability of this model for longer-lived components is less clear, given the likelihood of manufacturers ceasing trading before the circle closes (Schut et al., 2015).

The lifespan of buildings can also render the components themselves obsolete. Horvath (2004) poses a critical question of design that seeks to enable future benefits: how can reuse of building components be assured as feasible 'when it will become actual 30, 50 or 100 years from now?' Developments in materials, regulations, construction methods, and societal needs can create functional obsolescence of deconstructable buildings and reusable components; unexpected damage or wear can reduce integrity; tastes can change (section 1.2.3). For consumer products with a lifespan of, say, five years, future developments can more easily be

foreseen, and designers and manufacturers can be more confident in planning for end-of-life, but applying this thinking to the built environment produces dubious conclusions. Hansen (2016) champions an overhaul of building design: once buildings are conceived as a conglomeration of cradle-to-cradle products that can be used in continuous loops, their life cycle impacts will turn from simply being less bad, to being positive and 'eco-effective' (Braungart et al., 2007). This line of reasoning is appropriate to products with a fast replacement cycle, like mobile phones or carpet tiles, where improved design for end-of-life could have a relatively sudden and decisive impact. When product lifespan is only a few years, focusing on redesign could quickly create reusability and 'eco-effectiveness' across the bulk of the product population; feedback and learning can come sooner, and product design can evolve swiftly.

Replacement cycles in construction are far slower: average lifespans of existing buildings are reported to be 74 years in the USA and 132 years in the UK (Ma et al., 2015); half-lives of the German non-residential building stock are estimated at between 70 and 300 years, depending on the era of construction, and are even longer for housing stocks (Kohler and Yang, 2007); new build rates in the UK, Germany, Denmark, and the Netherlands are 0.5-1.5% per year (Bell, 2004; Hinnells et al., 2007; Power, 2010; van der Flier and Thomsen, 2006). Power (2010) calculated that 75% of the UK's 2050 housing stock had already been built. By the latter part of the 21st century, the segment of total end-of-life stock improved by design changes conceived now, will still be relatively modest (Poelman, 2009) – even if every new building is built according to DfD and circular economy principles. As with any anticipation of future benefits, the value of these improvements naturally carries a level of uncertainty (Hammond and Jones, 2011). Pomponi and Moncaster (2016) note that some circular economy thinking suffers from unwarranted faith in a technical fix: that 'having devised a solution implicitly means having solved the problem'. A technical solution to building deconstructability and component reusability unfortunately will not ensure actual reuse (Pomponi and Moncaster, 2016).

Carbon and resource criticality, and the continued use of primary resources in circular design

Most buildings built today will survive beyond the 'critical period for achieving global warming reduction targets set by [the UK] Government' (Kaethner and BurrIDGE, 2012). In view of this, and as far as the Climate Change Act (HM Government, 2008a) targets for 2050 are concerned, the end-of-life fate of today's new buildings has a limited influence. Nevertheless, it would be short-sighted to focus only on the Climate Change Act, and it is likely that resource scarcity will have become more critical by the time today's buildings reach end-of-life (Sassi, 2009: 239).

It is important to seek improvements to the end-of-life scenario that will apply to buildings beyond 2050; however, for the built environment to play its part in meeting the UK's obligations for 2050, we should adopt a more immediate focus on the existing building stock, demand reduction and the use of low carbon methods for new construction. The approach of *only* designing for future reuse, and not reusing materials today, fails to take enough responsibility for construction's current embodied emissions. Allwood (2014) questions whether a circular

economy is really possible or even desirable: 'if demand is growing, the circle cannot remain closed, and it may be a much more important priority to reduce the rate at which new material is required'. Allwood et al. (2017) build on the question of demand reduction. Their assessment of energy efficiency policy presents a useful analogy. They demonstrate that the current focus on supply side efficiency, such as generating energy from renewable sources, is futile: it cannot deliver the emissions reductions that are necessary to avoid dangerous levels of global warming. Instead, they show the necessity for reductions in demand that involve people within developed economies 'living well but differently'. Supply side measures that are invisible to consumers have a similar effect to the focus on design of new building stock: consumers still use as much energy, but it is generated in a different way; or still get new buildings, but they are designed to have lesser impacts. Because these approaches seek technical change 'behind the scenes', and do not require a fundamental change in consumption, they can only target a proportion of total impacts. They are attractive to governments because they avoid the political and sociological challenges of changing people's expectations.

At present there is considerable interest in the circular economy in relation to the built environment. A focus on new additions to building stock is justifiable, but by itself is not enough. It has no effect on today's waste generation; it overlooks the materials in the existing building stock and the resource this represents (Ness et al., 2005) – it does not address today's demand for primary resources or its impacts. Analogous to the demand side energy reductions discussed by Allwood et al. (2017), such as cars that are lighter and accelerate less quickly, is a reduction in demand for construction materials, by making do with existing buildings or existing components. Presently there appears little conviction in industry or society that it is possible to live well, but differently, by using secondary instead of primary building materials, or without carrying out demolition and redevelopment. Major challenges remain to test whether, and how, these changes are possible and to shift practitioner and public attitudes. These are the second and third areas of focus to address the global impacts identified in section 1.1.2.

1.2.3 Management of existing building stocks

The most significant decision in relation to the generation of waste and use of primary materials is whether to demolish an existing building, since 'the most environmentally benign building is the one that does not have to be built' (Moffatt and Russell, 2001). Management of the existing building stock, through intensifying use and prolonging lifespan (Haas et al., 2015), minimises the magnitude of resource inputs and waste outputs. Power (2010) identifies studies showing that new homes use up to eight times more resources than existing properties refurbished to achieve equivalent performance. However, the decision not to prolong lifespan, but instead to demolish, may be taken before the end of a building's physical service life (Bowes and Golton, 2001; Thomsen and van der Flier, 2009). Buildings may be deemed obsolete for a number of reasons. Packard's seminal work, *The Waste Makers* (1960: 55-56) describes three types of obsolescence:

- Functionality, i.e., progress made in technology such that older products are superseded: generally a positive phenomenon, though industry can sometimes artificially create functional obsolescence by lobbying for arguably unnecessary changes to standards that outdate older products;
- Durability, i.e., a product nears or reaches failure due to a physical fault (this is considered by Packard a negative aspect of industry, in making products that fail prematurely; though in construction, durability can be a genuine cause of failure through long-term wear);
- Desirability or 'emotional durability' (Chapman, cited in Harrod, 2013), i.e., a product is no longer appealing; considered by Packard a negative aspect of industry, in marketing newness and unnecessarily rebranding in order to outmode older products that are still functional and durable. Stahel (in Baker-Brown, 2017: xiii) holds that desirability is the primary determinant of longevity in construction.

Given the capital-intensive nature of construction, as well as existing buildings' societal and cultural significance (Thomsen and van der Flier, 2011) and the disruption to communities caused by their demolition (Power, 2010), one would expect every effort to be made to prolong lifespans. Functional obsolescence can to a great extent be addressed through retrofit and upgrading (e.g., insulating lofts, updating wiring). Durability can be extended through good maintenance and repair regimes. Desirability may be prolonged by refurbishment, or by more significant remodelling and adaptation.

In a study of the reasons for demolition in the context of Dutch housing, Thomsen and van der Flier (2009) show that in the past, 'building quality and public health played a decisive role in improvement of the housing stock, mainly by slum clearance', while more recently, 'functional and economic considerations tend to dominate the decision-making'. A similar trend is reported by Bowes and Golton (2001) in a study of the history of a site in Oldham in the northwest of England. 'Exogenous behavioural factors' (Thomsen and van der Flier, 2011) – such as poor liveability, social deprivation in the neighbourhood, and changing fashions – have a powerful influence over the decision to demolish. The prevailing view on the merit of certain building types at certain times influences their survival: the present perception of mid- to late-twentieth century social housing as socially divisive and of poor quality makes their demolition more acceptable. These factors are the result of wider societal trends; they are complex and changing. If 'slum' areas of Georgian London demolished for public health reasons had instead been maintained and upgraded, they would now be considered some of the most historically valuable and desirable types of property (Thompson, 1979). If buildings currently facing demolition partly for reasons of desirability were retained, they may yet be welcomed by a more receptive future society.

Seeking to extend the lifespan of existing buildings can have great environmental impacts, but typically these environmental factors are overshadowed by economic and other factors that are out of the control of the construction industry (K. Crawford et al., 2014; Gorgolewski and Ergun, 2013; Power, 2010; Thomsen and van der Flier, 2011). The economic factors that tend to influence the decision to demolish, such as land value and rental yield, are not considered within the scope of this project. From small parts of individual houses up to major regeneration projects, continued demolition appears inevitable, with the result that large quantities of building components will arise as waste. Even if existing building lifespans are maximised, there will be cases in which demolition (or deconstruction) is the only feasible option, as well as components removed during refurbishment. The third area of focus, therefore, and the one adopted in this project, is the management of components removed from the existing building stock.

1.2.4 Management of building components removed from stock

The waste hierarchy directs attention towards waste prevention, but lofty goals of 'eliminating waste' (Kibert et al., 2000; Lehmann, 2011) would appear to be irreconcilable with genuine forms of obsolescence and insoluble without addressing all the factors that make demolition a part of urban regeneration. Accepting that components will be removed from the building stock and attempting to use them wisely has been termed an end-of-pipe treatment (Ajayi et al., 2015), with the critique that it does not solve the problem at source. They see end-of-pipe treatments not only as sub-optimal, but as impediments to 'waste effectiveness'. A similar critique comes from Hansen (2016), who dismisses attempts to make new products out of current waste. Unless a reclaimed product can be used in multiple, continuous loops, she holds that this is 'still linear design'. Both of these viewpoints advocate redesign to avoid waste, but appear to overlook the real-world context of the built environment. As has been shown, current levels of demolition may be reduced, but there is no prospect of it ceasing altogether; while changing today's design holds only the *possibility* of benefits in the long term, with increasing uncertainty as longer-lived building elements are considered.

A further criticism that can be made of efforts to use discarded materials to good effect is that they legitimise wasteful behaviour. Developing an effective process for recycling disposable coffee cups makes the single-use item appear more acceptable, and potentially inhibits the take-up of environmentally preferable reusable cups. Arguably, in construction, mitigating the impacts of demolition waste removes responsibility from decision-makers, who are able to cite developer's sustainability reports showing high percentages of waste diverted from landfill. Without these options, though, demolition would in all likelihood proceed regardless: functional and economic considerations tend to dominate decision-making (section 1.2.3). On that basis, focusing on removals from stock is a pragmatic approach to the real needs of today's construction industry. It is unlikely to be circumvented by circular design, at least until the end of this century (by which point contextual developments will have made present speculations irrelevant). Recirculating existing building components for further use can reduce the amount of

material going into waste management and reduce the use of primary resources. Thus there is an immediate benefit in the realms of both input to, and output from, building stock.

McDonough and Braungart's (2002) statement that 'waste equals food' has become a founding principle of the circular economy. The metaphor's strength is in the attitude it imparts of recognising in waste an abundance of technical or biological 'nutrients': a source of potential performance that just needs to be exploited. This research urges an end to the dogmatism that considers only new design a legitimate contribution to circularity. If waste is food, it could emerge from the designed end-of-use of a circular product system, or it could be the unplanned result of historic design. Which is the major source will depend on the sector in question, the lifespan of goods and the timeframe of enquiry. For most construction industry component types in the present and near future, the existing stock is dominant. Seeing this waste as food encourages creative thinking about how existing components can best be used: for sustainability, in terms of mitigating the many impacts of construction; and for resilience, in terms of the industry's ability to adapt to changing circumstances.

Apart from downcycling, attention to materials removed from existing building stocks is presently limited to the architectural salvage industry, which provides some opportunity for contractors and demolition contractors to reclaim and sell building components. However, evidence suggests that the UK salvage industry is in decline in terms of quantities stocked, total value of trade, and number of people employed in the sector (CRWP and Salvo, 2007), partly as a result of competition from the recycling industries (BioRegional and Salvo, 2010). Increasing reuse of materials has been identified by the Centre for Industrial Energy, Materials and Products (CIEMAP) as the second biggest resource efficiency gain that could be made in construction, potentially achieving emissions reductions of 22.3 MtCO₂e between 2023 and 2032 (Green Alliance, 2018). Coupled with reduction in material inputs through design optimisation (8.93 MtCO₂e) and substitution of low carbon materials for high carbon materials (47.91 MtCO₂e), the scenario modelled for construction can reduce the projected emissions overshoot by more than 50% in the fourth carbon budget period (2023-2027) and by 40% in the fifth carbon budget period (2028-2032).

The scenario modelled by CIEMAP includes an increase in reuse of steel from 5% to 35%. Growing academic attention has focused on the reuse of structural steel, thanks to its ubiquity, the significant environmental benefits that would arise from shortcutting recycling, and the intuitive feasibility of deconstructing and reusing these relatively high-value components (section 2.4.3). However, the literature finds that the economic case for steel reuse is marginal (e.g., Dunant et al., 2018). The economic challenges seen with steel, and the narrow scope of products traded by salvage yards, suggest that a like-for-like model of reuse (e.g., timber floorboards reused as timber floorboards) is only viable for a select few building component types. Effective management of other less-valuable components may be supported by processes that not only *retain* their performance, but *enhance* it, to add value. Research exploring value-adding possibilities beyond like-for-like reuse is presently scarce.

'Upcycling' is a term that is growing in use (Sung, 2015), applied mostly in textiles and craft-type activities with individual objects. It has become particularly connected to the idea of repainting unloved items of furniture to give them a new lease of life – which unfortunately limits the application of the concept and gives it an air of DIY cheeriness – though its use originated in construction. In a 1994 interview, Reiner Pilz said: "Recycling, I call it down-cycling. They smash bricks, they smash everything. What we need is up-cycling, where old products are given more value, not less," (Kay, 1994). Upcycling is generally understood to refer to the enhancement of value or quality through non-destructive recycling. Unlike direct reuse, some processing is undertaken (for instance, in the form of removing parts or joining components together), but it is not a destructive process that returns the component to raw material (Allwood et al., 2011).

The increase in 'quality' achieved by upcycling has not been adequately defined, and its role in the management of components removed from the building stock has not yet been explored. This thesis has suggested that 'performance' can be thought of as a component's ability to perform a duty over a period of time. Maintaining performance can be achieved by extending the period of time that a component performs its duty, i.e., is reused in the same or another building, with little or no processing impacts. Increasing component performance would mean repurposing or upcycling a component such that it can perform a duty typically undertaken by a *different type of primary material with greater impacts* – and continue to be used in the same or another building. An upcycling process will have its own environmental impacts, which would need to be weighed against the increase in component performance (i.e., the displacement of primary production) that it achieves.

This begins to define what is meant by upcycling. The thesis explores the complementary roles of reuse, repurposing and upcycling in maintaining and increasing the performance of components removed from the building stock.

1.3 Project aim and objectives

1.3.1 Long term goal and project aim

This research investigates possible improvements to the management of existing building components; specifically, retaining or increasing the performance of components that are no longer needed to perform the duty in the building for which they were intended.

The envisaged route to change is development of academic knowledge of systems for building component reuse, repurposing and upcycling, such that, over time, this knowledge has the gravity and substance to influence policy and prompt innovations that are put into practice by industry actors, entrepreneurs, or university spin-out organisations.

To contribute to this long term goal, the project seeks to generate knowledge that sparks a new orientation towards valuing secondary materials. The aim of the project is to investigate, propose and test systems for reuse, repurposing and upcycling of existing building components.

1.3.2 Research scope, objectives and thesis structure

The research aim is undertaken through a predominantly qualitative mixed methods approach. The project begins in the locale of the industrial sponsors (Poplar HARCA and Tower Hamlets Homes; Appendix A) and their operations in the London Borough of Tower Hamlets. It develops theory about urban systems that could enable reuse, repurposing and upcycling of existing building components, and then, based on this theory, examines a practical case of using secondary timber as feedstock for cross-laminated timber (CLT). CLT is a structural building component formed of layers of timber laminated at right angles to one another. It is manufactured offsite in panels up to 16 m in length, 4 m in width and 300 mm thick, for use as wall, floor and roof elements. Commercial production began in the 1990s, and volumes have grown exponentially as CLT's market share has increased (Brandner, 2013).

The theoretical work at urban scale and the practical work at product scale are mutually supportive aspects of the thesis. The research objectives and sub-objectives in pursuit of the project aim are as follows.

Research objective 1: Describe what happens to building components at end-of-use; explain why the construction industry relies on waste management; and propose how a system of component management would differ.

- 1.1 Observe and investigate waste logistics, monitoring, attitudes and behaviours on construction sites and at waste transfer stations;
- 1.2 Reflect on and describe the systemic mechanisms that appear to influence management of end-of-use building components;
- 1.3 Propose alternative means of managing end-of-use building components in response to these systemic mechanisms;
- 1.4 Plan the steps, responsibilities and actions that could enable a transition to component management.

Research objective 2: Investigate how information about 'existing buildings as material banks' is currently obtained; propose means of improving information flows to support component management; and test how this could facilitate the emergence of reuse, repurposing and upcycling ideas.

- 2.1 Critically review existing practices and research that can contribute to an understanding of E-BAMB;
- 2.2 Examine the limitations of these practices for supporting reuse, repurposing and upcycling;

- 2.3 Show how new approaches to generating E-BAMB knowledge can address present shortfalls;
- 2.4 Discuss these proposals in the light of other relevant advances to illustrate a scenario for future knowledge of E-BAMB.

Research objective 3: Investigate the environmental implications of using secondary timber as feedstock for CLT; test the fabrication process and mechanical properties of cross-laminated secondary timber (CLST); and discuss the practical feasibility and economic drivers of a CLST enterprise.

- 3.1 Review the existing context of waste wood removed from building stocks and the present use of CLT in new construction;
- 3.2 Make CLST and cross-laminated primary timber (CLPT) at small-scale and examine their compressive and bending stiffness and strength;
- 3.3 Examine the potential effects of manmade defects and reduced properties of individual lamellae on properties of CLST;
- 3.4 Make recommendations for further research necessary to advance this concept to pilot-scale and commercial application;
- 3.5 Model the enterprise system that would produce CLST and use it to test the credibility of theories developed in pursuit of research objectives 1 and 2.

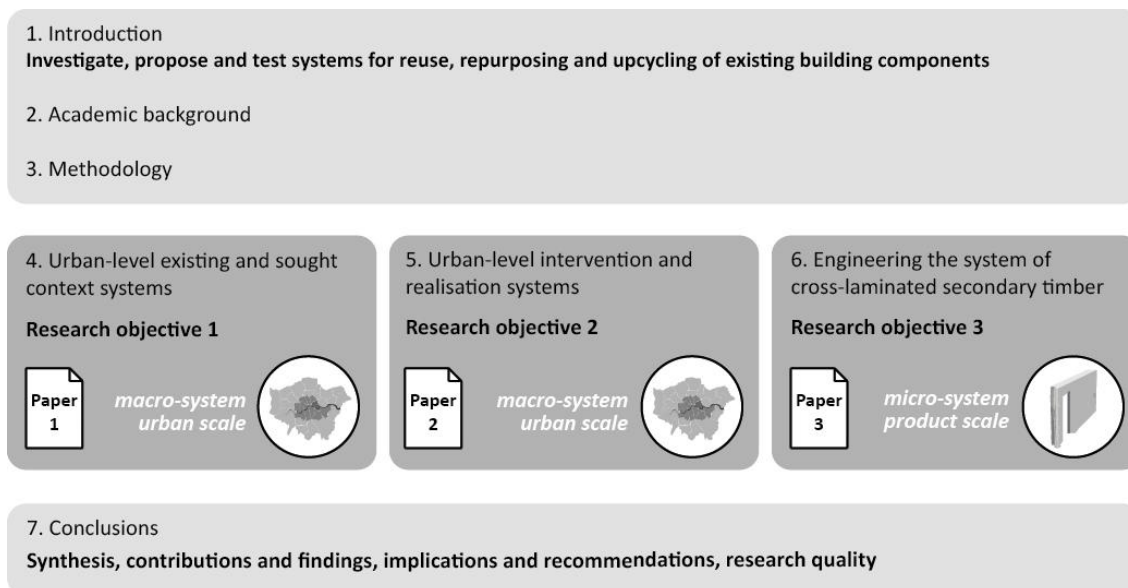


Figure 3: Thesis structure.

Figure 3 sets out the structure of the thesis. Chapter 2 critically reviews existing literature and Chapter 3 explains the methodology adopted in this project. Together, the opening three chapters establish the need to develop better management of existing building components to improve upon the global environmental impacts of the construction industry. Chapters 4 and 5

bring this perspective to bear on urban systems of component management. Chapter 4 addresses research objective 1 and Chapter 5 addresses research objective 2. They aim to contribute to knowledge that can inform policymakers, as well as advancing the academic field through a new emphasis on repurposing and upcycling as alternatives to direct reuse. Chapter 6 addresses research objective 3. It exemplifies an approach to existing building components by examining the case of CLST as a potential upcycled product and the notional enterprise that would bring it about.

1.3.3 Publications arising from this research

1. Rose and Stegemann (2018a), *From Waste Management to Component Management in the Construction Industry*, published in the MDPI journal, *Sustainability*. The present author's contribution to the paper was as primary author. The paper's introduction and review is an abridged version of sections 1.1 and 1.2 of the thesis, and the remainder of the paper is included in Chapter 4 of the thesis. The article's specific contributions include:

- Critical review of existing literature and waste interventions that seek to mitigate construction industry environmental impacts and bring about reuse of building components;
- Multiple case studies to examine systemic mechanisms that lead to components being discarded, such as the failure to identify components in advance;
- Development of a triage process to address identified flaws and separate out those components that can be reused, repurposed or upcycled;
- Identification of responsibilities for policymakers, clients, design teams, new upcycling enterprises and academia within the triage process, to increase capacity for component management and thus mitigate industry's environmental impacts.

2. Rose and Stegemann (2018b), *Characterising Existing Buildings as Material Banks (E-BAMB) to Enable Component Reuse*, published in the Proceedings of the Institution of Civil Engineers journal *Engineering Sustainability*. The present author's contribution to the paper was as primary author. The paper is included in Chapter 5 of the thesis with minor amendments to remove duplication. The article's specific contributions include:

- Critical review of existing practices and research that can contribute to an understanding of E-BAMB;
- Examination of the limitations of these practices for supporting reuse, repurposing and upcycling;

- Description of new approaches to generating E-BAMB knowledge that may address present shortfalls;
- Discussion of these proposals in the light of other relevant advances to illustrate how an E-BAMB information system could be formulated and strengthened in future.

3. Rose et al. (2018), *Cross-Laminated Secondary Timber: Experimental Testing and Modelling the Effect of Defects and Reduced Feedstock Properties*, under peer review at the MDPI journal, *Sustainability*. The present author is the paper's primary author, leading the topic's conceptualisation and rationale, coordinating investigations and others' contributions, writing the majority of the paper and editing. The paper draws together work conducted under the supervision of the primary author by Master's students, Evi Unubreme and Tianyao Lyu (experiments), and Thibault Dufresne (Finite Element Modelling; FEM), and includes Mechanically Jointed Beams Theory (MJBT) calculations that were designed, carried out and described by Dan Bergsagel of Scale Rule. Portions of the text that describe work that was undertaken primarily by a collaborator from a different discipline are reproduced in italics. The paper is included in Chapter 6 of the thesis with some additional sections that were removed in the submitted version. The article's specific contributions include:

- A carefully evidenced proposal for the use of secondary timber emerging from demolition to make CLST as an example of upcycling – an alternative to reuse (which is often impractical), or conventional waste management (which chips or incinerates wood and does not capitalise on the residual value and performance of solid timber);
- Preliminary research to explore the practical feasibility of making CLST;
- Preliminary investigation of the mechanical properties of CLST, using three complementary techniques:
 - experimental testing of the stiffness and strength of CLST and a control in compression and bending,
 - FEM of the potential effects of manmade defects on CLST stiffness in compression and bending, and
 - MJBT calculation of the potential effects of reduced secondary timber stiffness due to ageing on CLST stiffness in compression and bending;
- Identification of research questions for further work to advance the concept of CLST towards commercial application.

4. Romero et al. (2019), *Quantification of Material Stocks in Existing Buildings Using Serendipitous Data: A Case Study on Timber in a London Borough*, in preparation. The present author is the paper's secondary author, conceiving the study, providing access to sources of data, supervising investigations by the primary author, writing elements of the paper and reviewing. The paper develops a method for understanding the components in existing building stock with sufficient detail to inform reuse, repurposing and upcycling. The method is applied to the case of timber in residential buildings in the London Borough of Tower Hamlets. An abstract of the paper is included in Appendix B.

Conference contribution 1. Rose et al. (2015a), *Mining the construction process and our existing building stock: an assessment of current demolition and waste management practices and a triage process for resource valorisation*, delivered by the present author at WASCON 2015 – *Resource Efficiency in Construction* in Santander, Spain. The paper assesses current construction and demolition waste management based on multiple case studies. It introduces the triage process and identifies areas of intervention. The extended abstract is included in Appendix C.

Conference contribution 2. Rose et al. (2015b), *Viable and scalable reuse in construction: the case of upcycling waste wood to make cross-laminated timber*, delivered by the present author at UCL Urban Sustainability and Resilience *Research Showcase* in London, UK. The presentation discussed current management of wood waste, put forward the principle of CLST and reported the results of initial mechanical testing. The abstract is included in Appendix D.

Conference contribution 3. Rose and Stegemann (2016), *Triage: Designing a Materials Management Framework for secondary use of construction components*, delivered by the present author at EU COST Action *Mining the European Anthroposphere* in Odense, Denmark. The presentation discussed the triage process for separating out reusable components from materials to be sent to waste management, and reported on live case studies testing the triage in practice. The abstract is included in Appendix E.

Conference contribution 4. Rose and Stegemann (2017), *An urban triage for existing construction components entering the waste stream, and the case of cross-laminated timber upcycled from waste wood*, delivered by the present author at *Positions on Circularity in the Built Environment* in Munich, Germany. The presentation discussed the triage process and preliminary research to explore the feasibility and practicality of CLST, including pilot production by the author. The abstract is included in Appendix F.

2 ACADEMIC BACKGROUND

2.1 Introduction to literature review

The previous chapter set out the context of the construction industry's global impacts, and made clear that targeting future reductions of waste through the design of new circular additions to the building stock is not the focus of this study. Nor is the retention and adaptation of existing buildings. These are both crucial areas of research, but the scope of this study is limited to existing components removed from the building stock. This chapter reviews previous academic work that has attempted to address the same topic. The review is organised into research on *quantities* of waste, *management options* and their preference order, and *increasing reuse* by identifying and addressing barriers. It then builds a rationale for *repurposing and upcycling* as alternative waste management options. It aims to establish what has so far been done and achieved, with what specific goals; what is missing; and what inadequacies remain.

Some of the terms around this subject are used interchangeably, or have more than one usage. To avoid confusion a Glossary of terms is provided after the Appendices to set out the ways in which terms will be used in this study.

2.2 Quantifying C&D waste generation

2.2.1 Distinguishing construction waste and demolition waste

Most quantification studies cover both construction and demolition waste. Construction waste comes about from the act of building: it includes offcuts, by-products (such as sawdust), leftovers (such as mortar), surplus (unused new materials and products), goods damaged on site, and completed work that is wrong for some reason (lack of clarity in construction information, late design changes and so on). In an investigation into three case studies (CRWP, 2008), these were found to be the most common types of construction waste. Elsewhere, packaging has been reported as a major constituent and temporary works that are part of the construction process, such as formwork, are another contributor (CRWP, 2009; Envirowise, 2006; Hobbs, 2011: 126). As explained in section 1.2.2, construction waste has its own body of literature and set of mitigating strategies, which this study does not intend to reprise. Up to a point, designers and contractors are able to control construction waste generation, and attempts to prevent or minimise it are a higher priority than improving the way it is managed.

However, where construction waste arises in spite of minimisation efforts, it enters the same waste management system as demolition waste. This thesis focuses on the waste management system with a view to improving the use of existing building components; the

same approach could enable better use of construction waste, but this should not detract from prevention strategies.

2.2.2 C&D waste generation and material recovery in grey literature

An idea of the magnitude of UK C&D waste generation and amount diverted from landfill can be gathered from published national statistics (Defra, 2016, 2015, 2012a). These weight-based estimates follow a method in compliance with data reporting requirements of the Waste Framework Directive (WFD; European Commission, 2018, 2008). They are derived from waste returns by waste transfer and treatment stations (required by the Environment Agency to assess stations' compliance with environmental permits); waste returns by landfill operators; and data collated by Mineral Products Association members on generation of recycled or secondary aggregate produced from C&D materials (Defra, 2012b). The data published from 2012 to 2016 show UK C&D waste generation varying in correlation with the state of the economy and extent of industry activity (BRE and WRAP, 2012; Hobbs et al., 2011), and the material recovery rate rising slowly towards 90% (Table 2).

Table 2: UK generation and recovery of non-hazardous construction and demolition waste

	Generation (Mtpa)	Recovery (Mtpa)	Recovery rate	Source
2008	58.1	50.6	87.1%	Defra, 2012a
2009	47.8	41.7	87.3%	Defra, 2012a
2010	49.5	43.4	87.6%	Defra, 2016
2011	50.0	43.8	87.6%	Defra, 2016
2012	51.2	45.3	88.6%	Defra, 2016
2013	51.9	46.6	89.8%	Defra, 2016
2014	55.0	49.4	89.9%	Defra, 2016

Excludes excavation waste and hazardous waste

Defra (2016) state that accurately quantifying C&D waste is challenging, and acknowledge that the absolute mass figures are subject to a high level of uncertainty (although it is claimed that this uncertainty does not have a significant impact on confidence in recovery rates). The findings in Table 2 suggest internal coherence within Defra's method from year to year, but statistics from other sources sometimes conflict, with confusion arising from the inclusion or exclusion of excavation waste. As an alternative, reporting and analysis of waste leaving individual construction sites can provide a bottom-up portrayal of waste arising. BRE's SMARTWaste tool helps contractors prepare site waste management plans, and functions as a feedback mechanism, enabling the collection of data from thousands of completed projects (BRE, 2013). These are used to establish benchmarks, check performance against benchmarks, improve future forecasting (which would allow contractors to tender for work more accurately), and identify strategies for minimising future waste (Hobbs et al., 2011).

2.2.3 C&D waste generation and projections in academic literature

Academic work that quantifies waste on a project basis or a regional basis has been reviewed by Wu et al. (2014). They explain the different methods that have been employed to arrive at estimates of current or forthcoming C&D waste. For instance, a study by Bossink and Brouwers (1996) uses case study building projects in the Netherlands to quantify the proportion of different building components emerging as waste from construction, by mass and by cost. Depending on the component type, 1-10% by mass of the purchased goods leave site as waste. Drawing on previous research from several European countries, they find that demolition waste typically amounts to between two and five times the quantity of construction waste, by mass. This finding is corroborated by Bergsdal et al. (2007), who show that demolition waste makes up the majority of C&D waste in Norway. They go on to use waste generation factors and building lifespan analysis to make projections of future flows of materials out of the building stock and into waste management. Their results predict increases in C&D waste, with figures for different materials; they anticipate that this will inform investment in waste treatment capacity. Material flow analysis underpins much of the work in this field (Tanikawa et al., 2002). By looking at societal use of materials in building stocks en masse, these studies can shed light on long-term expected waste trends. In response to research that shows continual growth in stocks in all countries studied (Hashimoto et al., 2007), Müller (2006) developed a model for stock dynamics to forecast both waste generation and resource demand in Dutch housing.

In the attempt to describe the totality of in-use stocks, studies frequently arrive at overall tonnages of material per capita (e.g., Tanikawa and Hashimoto, 2009; Wiedenhofer et al., 2015). Such figures allow high-level comparison between countries (Vásquez et al., 2016), but the economy-wide breadth of investigation means that the data have little practical application at project level. Most of the materials assessed will remain locked up in use for decades. Technical and cultural challenges of implementing the findings to bring about positive change are rarely addressed (Wallsten, 2015). To support component reuse, there is a need for a closer and more detailed focus on the qualitative nature of materials emerging from the building stock.

2.3 Order of preference for C&D waste management options

2.3.1 The waste hierarchy

The WFD (European Commission, 2018, 2008) is the overarching current legislation that governs how EU Member States manage all waste. Its provisions are transposed into UK law through the Waste (England and Wales) Regulations (HM Government, 2011). The WFD embeds into law the older principle of 'reduce, reuse, recycle' (Van Ewijk and Stegemann, 2016) as the waste hierarchy (Table 3). Its preferential order must be followed, unless

‘departing from the hierarchy [...] is justified by life-cycle thinking on the overall impacts of the generation and management of such waste’ (European Commission, 2008: Article 4). The integrity of the waste hierarchy is weakened by the inclusion of ‘technical feasibility’ and ‘economic viability’ as conditions to any such justification. If it is allowable to bypass higher preference options like ‘preparing for reuse’ when that route can be portrayed as not ‘economically viable’, then waste management decision-making is left at the behest of economics (Santos and De Brito, 2005; Van Ewijk and Stegemann, 2016).

Table 3: Representation of the waste hierarchy, with priority order from highest to lowest

Activity	Definition	Acts upon	Specific C&D targets
Prevention	<p>‘Measures taken before a substance, material or product has become waste, that reduce:</p> <p>(a) the quantity of waste, including through the re-use of products or the extension of the life span of products;</p> <p>(b) the adverse impacts of the generated waste on the environment and human health; or</p> <p>(c) the content of harmful substances in materials and products;</p> <p>‘re-use’ means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived’</p>	Substance, material or product (non-waste)	None
Preparing for reuse	‘Checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing’	Waste	Included in material recovery, minimum 70% by weight by 2020; possible target for reuse and recycling after 2024
Recycling	‘Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes’	Waste	Included in material recovery, minimum 70% by weight by 2020; possible target for reuse and recycling after 2024
Other material recovery, ^a e.g., backfilling	‘Any recovery operation, other than energy recovery and the reprocessing into materials that are to be used as fuels or other means to generate energy’	Waste	Included in material recovery, minimum 70% by weight by 2020
Other recovery, e.g., energy recovery	‘Energy recovery and reprocessing of waste into materials used as fuels or other means to generate energy’	Waste	None
Disposal	‘Any operation which is not recovery’, including landfill and incineration without energy recovery	Waste	None

^a Definition of ‘material recovery’ introduced in WFD amendments (European Commission, 2018)

A definition of 'material recovery' is introduced in the recent amendments to the WFD to clarify the target (European Commission, 2018). Material recovery is a general term, of which preparing for reuse and recycling are special cases. It includes backfilling and other forms of material recovery such as road construction, but excludes energy recovery. The UK and several other member states have long since surpassed the 70% target; at present there is little legislative impetus to improve C&D waste management from general 'material recovery' to the higher levels of the waste hierarchy (Adams et al., 2017). The setting of a separate target for 'preparing for reuse and recycling of C&D waste and its material-specific fractions' is to be considered by the Commission by 2024 (European Commission, 2018). Perhaps in preparation for that change, the amendments to the WFD call for member states to begin reporting the amount of waste used for backfilling and other material recovery operations separately from the amount of waste prepared for reuse or recycling.

2.3.2 The definition of waste

The WFD sets out the definition of waste: 'any substance or object which the holder discards or intends or is required to discard' (European Commission, 2008: Article 3). Once a component is legally classified as waste, it is subject to regulations that inhibit its use. Businesses have a duty of care to consign their waste to a registered carrier and understand its fate; all handling and trading of waste must be carried out by registered carriers and brokers; and to be 'recovered' it must meet end-of-waste criteria, which are yet to be specified for many types of construction waste (Defra, 2007b; European Commission, 2008; HM Government, 2011, 1990). It is far from clear that reclaimed building components that are not environmentally harmful, and are suitable for reuse, should be deemed waste and subject to these restrictions.

The new UK Resources and Waste Strategy is due to be released by the end of 2018 (HM Government, 2017: 135). Recent work by the Aldersgate Group (2018) that aims to inform its preparation, and industry recommendations by Symons and Baker (2017), advocate a 'pragmatic application' of waste regulations. They propose that materials should not be classified as waste unless no other safe use can be identified.

2.3.3 The definitions and benefits of prevention and reuse

Whether or not such a change is enacted, the existing definition of prevention includes 'the re-use of products or the extension of the life span of products' (European Commission, 2008: Article 3(12)). Reuse, as a prevention strategy, is not a waste treatment operation (though it can be difficult to tell apart from the waste action 'preparing for reuse'; interpretations of the WFD provisions vary; Arcadis, 2010: 42-43; Corvellec and Czarniawska, 2014). An effective waste prevention scheme would include interventions that pre-empt the need or intention to discard, and thus avoid components becoming waste (Zacho and Mosgaard, 2016). In C&D, this might mean demonstrating to contractors and demolition contractors that there is demand

for end-of-use components they produce, to encourage them not to discard but to recirculate products in other markets.

When acting on waste or on non-waste, reuse allows the embodied impacts in existing building components to be retained, providing a low carbon alternative to primary materials if employed in new buildings (Geyer and Jackson, 2004; Thormark, 2000). The distance that reclaimed materials are transported is an influential factor on both cost and environmental impact; this should be assessed in each case but typical maximum travel distances have been calculated for different component types (Howard and Anderson, 2000; Thormark, 2000). By extending a product's lifespan, reuse can delay the processing impacts of recycling and transportation of materials to and from recycling plants. This life extension should not impede the future ability to recycle the product once reuse is no longer feasible (Thormark, 2002; Zygomalas and Baniotopoulos, 2015). Reuse can also add social value, for instance through training and jobs that are more skilled and more numerous than those in recycling, energy recovery or disposal (BioRegional, 2009; Gorgolewski, 2008). The inherent localism of recirculating existing building components provides opportunities for more local spending, which, in the mould of what has become known as the 'Preston model' (Manley, 2017), could help to regenerate post-industrial towns, cities and regions.

The WFD defines reuse as a process of using products or components again for the same purpose for which they were conceived (European Commission, 2008: Article 3(13)). There is debate on the limitations of this definition. Arcadis (2010: 44, 226-228) consult several European legal organisations and trade associations to seek views on whether reuse could include using a product for a different purpose to the original intention, i.e., repurposing. They report that some consider repurposing a form of reuse, as long as there were no other adverse environmental impacts, while others adhere to the letter of the WFD and would not consider secondary use for a different purpose within the definition of reuse. A rigid interpretation of the WFD is unhelpful in the situation of a building component that has become obsolete for its original purpose, but can be put to a different purpose without processing. An example is a single-glazed window that could be repurposed as part of an internal partition. Given that this is a different purpose to that for which it was originally conceived, it cannot strictly be deemed 'reuse'. The waste hierarchy fails to steer the waste producer towards the repurposing option in preference to sending the window for recycling. Moreover, enterprises pursuing business models that add value to waste through simple repurposing would not be supported by the hierarchy's preference order, despite the environmental benefits they could bring.

A limitation of the definition of preparing for reuse is that it allows only minor checking, cleaning and repair operations (European Commission, 2008: Article 3(16)). This ensures that reuse activities have very low environmental impacts, in contrast to the sometimes significant impacts of recycling (Chong and Hermreck, 2010). However, remaining within this narrow scope creates barriers to reuse based on the impracticality of directly employing many reclaimed components (e.g., Gorgolewski and Ergun, 2013; Hemström et al., 2012; see section 2.4.1). They may have

undergone significant damage, be in short lengths when long lengths are needed, be too large to incorporate into design unless considered from the outset; they may not comply with current regulations, or suffer some aesthetic or perceptual drawback. Restricting what is allowed under 'reuse' means that simple processes that could address these problems – such as significant repair, joining together small pieces, breaking down unwieldy components, upgrading to meet current regulations, or adapting to improve perception – are not distinguished from conventional recycling in the waste hierarchy. It provides no impetus for waste producers to seek these simple processes rather than discarding to waste management and allowing components to be reduced to raw materials.

2.3.4 Problems with recycling and downcycling

Why is the construction industry's reliance on recycling unsatisfactory? Firstly, the often globalised transportation and processing involved in recycling makes even a closed loop recycling system energy intensive (Allwood et al., 2012; Chong and Hermreck, 2010; Cullen, 2017). It is argued that energy supplies can be decarbonised, but the development of low carbon energy generation options looks unlikely to meet global energy consumption or be deployed sufficiently rapidly to avoid dangerous levels of global warming (Allwood et al., 2017). Secondly, performance of recycled products is achieved by introducing primary materials and there are material losses during processing (Allwood, 2014; Allwood et al., 2013; Cullen, 2017; Dixit et al., 2013; Lanfang et al., 2015; Moriguchi, 2007; Sassi, 2008). Thirdly, recycled materials can create new low-priced alternatives and greater overall consumption, without reducing the demand for primary materials (Haas et al., 2015). An example of the failure of recycling to displace demand for primary materials in construction is reported by Schut et al. (2015): only three percent of the materials used to construct buildings in the Netherlands are from a reused or recycled source, despite 95% of C&D waste being recycled. Vast amounts end up as material for road bases, while new construction continues to draw on primary resources. This is an extreme case of downcycling, from high quality concrete and masonry to low quality road base.

The amendments to the WFD introduce a welcome new emphasis on 'high-quality recycling'; for example, member states must

take measures to promote selective demolition in order to enable removal and safe handling of hazardous substances and facilitate re-use and high-quality recycling by selective removal of materials, and to ensure the establishment of sorting systems for construction and demolition waste at least for wood, mineral fractions (concrete, bricks, tiles and ceramics, stones), metal, glass, plastic and plaster. (European Commission, 2018: Article 11(1))

'Selective demolition' is used synonymously with deconstruction in the academic literature. It is positive that this idea has penetrated European legislation as a means of facilitating reuse and high quality recycling. The appeal to high quality recycling in this paragraph, and others, suggests progress towards consideration of the actual benefits of different recycling processes;

further, it could feasibly evolve into the separation of recycling and downcycling in a future revision of the waste hierarchy. At present the WFD presents no definition of quality, or explanation of how high and low quality recycling processes would be distinguished or delineated.

2.4 Increasing reuse: barriers and strategies to overcome them

2.4.1 Review of barriers reported in the literature

What constraints appear to act upon industry to prevent the processes involved in building component reuse from happening? Considerable scholarly effort has been put towards the identification of constraints, using methods including expert interviews, surveys and observational case studies. Different researchers identify barriers that are either subtly or significantly different parts of the problem. This section reviews publications by authors who are explicitly seeking to identify barriers to the uptake of reuse, rather than, for instance, uptake of low carbon materials in general (Giesekam et al, 2014; 2015); or of recycled materials (Chick & Micklethwaite, 2004; Zoe et al, 2015). From the DfD literature (e.g., Densley Tingley, 2012), this review reports those barriers relating to deconstruction of existing buildings, as this is critical to the provision of materials, but barriers to *design for* deconstruction are outside of this review's scope. The identified barriers are categorised under three headings: reclamation (the extraction of components from existing buildings as part of demolition, deconstruction or soft strip), reverse logistics (the flow of reclaimed components to their new point of use) and reuse (their application in a new project).

Reverse logistics is more commonly associated with manufacturing, but has been adopted by construction industry researchers as a concept for end-of-use building components. It is understood as 'the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of creating or recapturing value, or proper disposal' (Rogers and Tibben-Lembke, 1999, cited in Hosseini et al., 2014). Reverse logistics is a 'venous industry', as opposed to the 'arterial industry' responsible for production and supply (Fujita and Iwata, 2008). Hosseini et al. distinguish reverse logistics from waste management by the criteria of value: reverse logistics gathers only products and materials 'with value', since recapturing value is intrinsic to its definition. Reading this as economic value, rather than usefulness, there is an assumption of *a priori* knowledge of what does and does not have value in a given market. This is context-dependent and dynamic, and therefore difficult to operate as a rule; it also seems an unnecessary curb on the potential feedstock that reverse logistics operations could deliver for new value-adding processes.

By its strict definition, reverse logistics is concerned with the *movement* of materials, rather than their eventual use or processing (which, in the terms used in this field, is secondary ‘forward logistics’). However, since its goal is creating or recapturing value, it follows that scholars in this field would not be indifferent to what happens *after* the movement of materials back to their origin, or another place of recirculation. This is borne out in work by researchers at the University of South Australia, Adelaide, who purport to identify barriers to reverse logistics in the construction industry, but also identify barriers to high-value reuse (e.g., Rameezdeen et al., 2015). To the extent that these papers report barriers experienced in the construction industry in general – rather than only in their specific geographical context – they are useful companions to this review. In particular, a systematic review of barriers by Hosseini et al., (2015) captures findings from 40 studies published worldwide. Their article provides a list of barriers that match many of those found in this review. Table 4, Table 5 and Table 6 bring together Hosseini et al.’s list, with a set reported in a review of seven papers by Densley Tingley (2012), and additional barriers from a further fifteen papers not included in the earlier reviews.

Overview

This review now spans almost twenty years – perhaps long enough to expect work from the earlier times to have had an impact on practice – yet the barriers reported in recent studies are similar to those identified in the early 2000s. Table 4, Table 5 and Table 6 indicate no clear trend of earlier barriers disappearing or new barriers arising over time. Some are unavoidable: ‘buildings not designed/built for deconstruction’ (identified in 21 out of 62 reviewed publications); this relates to the nature of the existing building stock, and changing this situation is the much longer-term project of DfD and the circular economy.

Over the studied time period, the UK Landfill Tax has increased rapidly, such that ‘availability of cheap waste disposal’ is generally no longer identified as a barrier in a UK context; though in a study across six European countries, Hemström et al. (2012) found cheap waste management is still a barrier. Simplicity of waste disposal, combined with lack of reverse logistics infrastructure, may also continue to act as a constraint on contractor’s willingness to support reuse through reclamation.

Table 4: Barriers to reclamation reported in the literature, developed from Hosseini et al. (2015) and Densley Tingley (2012)

BARRIERS TO RECLAMATION	Guy and Ciarimboli, n.d.	Dolan et al., 1999	Kibert et al., 2000	Catali and Williams, 2001	Crowther, 2001	Crowther, 2002	Hurley et al., 2002	Sassi, 2002	Chen et al., 2003	Chini and Bruening, 2003	Pulaski et al., 2003	Storey and Pederson, 2003	Addis and Schouten, 2004	Greer, 2004	O'Brien et al., 2004	Sassi, 2004	Horvath, 2004	Dantanta et al., 2005	Hurley and Hobbs, 2005	Morgan and Stevenson, 2005	Pun et al., 2005	Addis, 2006b	Addis, 2006a	Guy et al., 2006	Leigh and Patterson, 2006	Schultmann and Sunke, 2007a	Schultmann and Sunke, 2007b	Smith et al, 2007	Gorgolewski, 2008	Sassi, 2008	da Rocha and Sattler, 2009	Nordby et al, 2009	Denhart, 2010	Moore, 2010	Razaz, 2010	Sinha et al, 2010	Allwood et al., 2011	Coelho and de Brito, 2011	Hiete, 2011	Ali, 2012	Densley Tingley & Davison, 2012	Hemström et al., 2012	Kibert, 2012	Shakantu and Emuze, 2012	Srour et al., 2012	Gorgolewski and Ergun, 2013	Vaughan, 2013	Ajayi et al., 2015	Anggadajaja, 2014	Durmisevic and Binnemars, 2014	Earle et al., 2014	Hradil et al., 2014	Jaillon and Poon, 2014	Kuehlen et al., 2014	Nakajima, 2014	Nakajima and Russell, 2014	Cruz Rios et al., 2015	Joce, 2016	Bergsagel, 2016	van Battum, 2016	Adams et al., 2017	Dunant et al., 2017																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																											
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Key to colours:

Papers reviewed and barriers identified by Densley Tingley, 2012; consult original study for references

Papers reviewed and barriers identified by Hosseini et al., 2015 (their barrier numbering shown bold in brackets); consult original study for references

Additional papers reviewed and barriers identified in this study

Table 5: Barriers to reverse logistics reported in the literature, developed from Hosseini et al. (2015) and Densley Tingley (2012)

[illegible]

Key to colours:

Papers reviewed and barriers identified by Densley Tingley, 2012; consult original study for references

Papers reviewed and barriers identified by Hosseini et al., 2015 (their barrier numbering shown bold in brackets); consult original study for references

Additional papers reviewed and barriers identified in this study

Table 6: Barriers to reuse reported in the literature, developed from Hosseini et al. (2015) and Densley Tingley (2012)

[illegible]

Key to colours:

Papers reviewed and barriers identified by Densley Tingley, 2012; consult original study for references

Papers reviewed and barriers identified by Hosseini et al., 2015 (their barrier numbering shown bold in brackets); consult original study for references

Additional papers reviewed and barriers identified in this study

Barriers to reclamation

Two of the most commonly reported barriers to reclamation, alongside difficulties inherent to the existing building stock, are cost constraints related to the time required for deconstruction (22 out of 62), and programme constraints related to tight scheduling of site works (18 out of 62). Increasing the time available for soft strip and deconstruction is within easy reach of property owners, although possible underlying causes may also need to be addressed. For example, if demolition is perceived as a public nuisance, owners may set tight programmes in an effort to minimise adverse publicity (Hurley and Hobbs, 2005). Public and client recognition of the environmental and social benefits of deconstruction would help to distinguish it from the 'nuisance' of demolition.

Barriers to reverse logistics

Where the existing building stock does yield reusable components, there are challenges facing designers and contractors who may seek to use them in mainstream construction. 'Lack of reuse market, supply chain infrastructure and technology' is the most commonly reported barrier to reverse logistics (22 out of 62). In the absence of infrastructure for reused materials other than architectural salvage, the reverse logistics process would appear to be limited to sorting and storing components on site – itself identified as a cost and spatial constraint, especially in urban areas – and then transporting selected components to another site, where they are to be used. There is a question of how this selection process would come about if the demand side of the transaction lacks awareness of potential supply and is without information about available components, as reported in several studies. More fundamentally, the direct transfer of components from one site to another leaves the demand project fully exposed to the risks of 'insufficient quantities of components', 'inconsistent quality' and 'lack of performance guarantees'. These uncertainties over quantity and quality are likely to be closely linked to 'risk in specifying reused components', concerns about 'additional construction complexity' and 'insurance constraints'. The development of reuse markets and supply chain infrastructure therefore has the potential to address several linked barriers to reuse by increasing confidence in component quantities and quality. The extent to which it can address them depends on the scope of activities undertaken by intermediaries in such an infrastructure; for instance, carrying out tests and providing warranties.

Barriers to reuse

Many of the publications note that existing codes and standards are composed based on the properties of new materials, and therefore encourage their use. An advocate for reuse (and effective spokesperson for the salvage industry), Thornton Kay, suggests this is not as significant a barrier as commonly thought: the UK Building Regulations, Regulation 7 (Materials and workmanship), allows the use of any material, as long as it is fit for purpose (BioRegional and Salvo, 2010; Salvo News, 2013). This is typically achieved by certification (Hurley and

Hobbs, 2005), but that is not the only route to demonstrating fitness for purpose. Making specific reference to clauses in Regulation 7, Kay establishes that a) building control bodies should not impede the use of materials that are suitable for an intended purpose, and b) past experience, such as use in an existing building, can be used to demonstrate suitability (HM Government, 2013; Salvo News, 2013). Nonetheless, there is a burden on a member of the project team to make the claim of fitness for purpose, and if suppliers, specifiers and contractors show reluctance, as the research suggests, client confidence will remain low. Private homeowners purchasing reclaimed materials from salvage yards may be reassured, but for mainstream construction organisations and their insurers, some form of certification is the norm. Obtaining certification and providing warranties equivalent to primary products will be challenging (Chileshe et al., 2015; Joce, 2016), but in many circumstances, necessary, if secondary components are to be adopted by a risk-averse construction industry (Gieseke et al., 2014; Jones et al., 2016).

The cost of new materials is mentioned surprisingly rarely as a barrier to reuse. Elsewhere in the literature, it is pointed out that new materials are produced with extraordinary economies of scale and supplied at very low cost (e.g., Allwood, 2014). Without an established supply chain for reclamation and reverse logistics, each instance of reuse is at present a one-off transaction, with no economies of scale. The resulting cost uncertainty is compounded by the prevailing attitude towards reuse: a negative 'perception of second-hand materials; people prefer new'. If the perception is that people would rather have new materials, and they are cheaper, why risk doing something different? Recent years have seen an upsurge in an aesthetic of reclaimed and 'upcycled', and waste issues are growing more and more prominent in public discourse, but this appears to be still some distance from influencing specification and purchasing decisions in mainstream construction.

2.4.2 Systemic nature of the problem

The studies reviewed in the previous section report empirically observed barriers, but make relatively little attempt to understand the generative mechanisms and underlying structures that may be producing them. This is unlikely to provide the most fertile ground from which to develop interventions. 'Solutions' that aim to overcome individual barriers without an analysis of their cause are unlikely to succeed. Addressing one barrier may lead to the appearance of another, in the form of an unintended consequence or an unforeseen difficulty in implementation. For example, pre-demolition audits were introduced to help client teams and contractors to achieve the intentions of the waste hierarchy when considering options for existing building components from a forthcoming project (ICE, 2008; WRAP, 2005). By providing a framework for users to audit existing buildings, they would overcome information and awareness barriers and enable greater reuse. Positively, the use of pre-demolition audits has been incorporated into national and local planning guidance documents (ICE, 2008) to help their integration into the process of building procurement. However, in practice, pre-demolition

audits are often treated as a bureaucratic exercise, and not given the time they require to have impact on decisions made on site (Carris, 2011; Hurley, 2002). Why would this be the case?

At a workshop convened by the Alliance for Sustainable Building Products (ASBP, 2016), the issue of pre-demolition audits' timing was raised: the incentive to carry them out is linked to BREEAM, but because BREEAM assessment does not require the audit until later in the process, opportunities for reuse may not be considered until it is too late for them to be implemented (pers. comm. Cheshire, 2016). A new barrier could be perceived as the timing of the audit, or how it is orchestrated through the BREEAM assessment process. Addressing these could solve the problem – or may lead in turn to new barriers. Instead, or as well, it may be constructive to take approaches that search 'behind' empirically observed barriers. An example could be applying organisational behaviour change principles (Michie et al., 2011, in Jones et al., 2016) to consider whether clients and contractors recognise any benefits to pre-demolition audits other than the BREEAM credit; such an analysis may suggest changes are needed elsewhere to increase their motivation.

Developing standalone solutions that do not address the systemic nature of the problem may give the unhelpful impression that barriers are being addressed, while the longer arc of events suggests that reuse remains rare, downcycling predominant, and primary resource use unwaveringly high. Drilling down into perceived barriers to diagnose layers of possible causation could shed light on interventions that are likely to be effective. One root cause of many of the perceived barriers is likely to be the relative cost of new materials and labour. Generating a rich understanding of possible layers of causation creates the opportunity for a more reasoned allocation of researchers' and policymakers' attention between 'surface' barriers (e.g., designers' awareness of potential to reuse), generative mechanisms (e.g., the factors influencing contractors' motivation to fully engage in a pre-demolition audit), and underlying structures (e.g., the economics of labour and resource use).

2.4.3 Industry-focused strategies to address reported barriers

Two studies that are representative of research investigating various possible industry-level strategies to increase reuse are Hemström et al. (2012) and Adams et al. (2017). Both develop their findings from consultation of a range of industry stakeholders, Hemström et al. using interviews and workshops with participants from Sweden, Germany, Belgium, Poland, Italy and Spain, and Adams et al. using a quantitative online survey and a focus group in the UK. Both take the approach of identifying probable barriers and suggested means of overcoming them. The study by Adams et al. demonstrates a common trait of papers on this topic: it spans reuse of existing building components and future reuse of today's new components. There is crossover between these areas, especially where lessons about characteristics of the existing building stock that make it difficult to recover components are conveyed from the waste industry to designers. However, the value of this crossover is limited, and the sweep of the survey, across a wide range of possible 'enablers for implementing circular economy' clouds the focus

of the study. Strategies that cannot be applied to the existing building stock, such as DfD tools and guidance and product take-back schemes, are presented alongside 'financial incentives to use secondary materials'. As a result, it is unclear whether other proposed enablers such as 'best practice case studies' and 'a clear business case' are intended to enable reuse of existing components, new business models and design for future reuse, or both. The reporting of survey responses and focus group discussions flits between the two topics, as well as mentioning the importance of refurbishment to extend building lifespan. The lack of framing around a single topic appears to have led to research participants voicing the current preoccupations of industry, which lean more towards business models and design for future reuse. 'Circular economy in construction' is too broad a subject; in the attempt to present a comprehensive view, the study does not address any part of the subject in depth.

The paper by Hemström et al. (2012) is more definitively focused on the fate of components from the existing building stock, allowing the authors to interrogate more facets of this particular problem. They set out a coordinated assessment of the barriers and opportunities in firstly, increasing the supply of reusable products, and secondly, increasing the demand for reusable products. These findings are drawn together in a commentary on interventions that could facilitate reuse.

Reverse logistics infrastructure

They suggest that a network of storage and redistribution centres for reused components ('reuse points') is a prerequisite of an 'optimal' system. They suggest a number of ways to organise such a network, in both the public and private sphere, but they emphasise the role that could be played by a 'key facilitating actor', such as a reuse-oriented industry association. This organisation could develop assessment methods for reused components and work towards their inclusion in CE marking: an important enabler also identified by Adams et al. (2017). Hemström et al. report that such a system has been requested by reuse agents, architects and contractors, to build confidence in reused components. They suggest that this may need support at construction sector level or at European level.

Adams et al. (2017) see the establishment of secondary markets as a possible means of ensuring that adequate quality and quantities are available to specifiers and contractors, but make no recommendations as to how this could be implemented. The reuse-oriented industry association proposed by Hemström et al. could have a role to play in operating such an intervention: they suggest that the association manages a 'coordinated database system'. They envisage this linking together the network of reuse points and improving the liquidity of components in storage or yet to be removed from the building stock by providing information needed by potential buyers (e.g., product type, quantity, dimensions, quality and performance, location and timeframe). It is an idea that various researchers have investigated, and the literature is explored in section 2.4.4.

Reused product information

In terms of further academic work, Hemström et al. (2012) suggest research on the practical reusability of specific components and inventories of in-use stocks, which could help to identify secondary supply opportunities; and LCA of feasible options to increase demand from those designers and clients for whom sustainability is a driver. Adams et al. (2017) also note the importance of whole life cycle metrics, but place this within the remit of business in producing Environmental Product Declarations (EPDs) under CEN/TC 350. Their study calls for 'circularity metrics' that can form a part of the information sharing capabilities of BIM. It is likely that focus group participants had new products in mind during these discussions. Ultimately the reused product sectors should aim to integrate with BIM and demonstrate their environmental performance through the common currency of EPDs, but in the short term BIM integration and the requirement for EPDs are more likely to act as constraints on reuse. As specifiers require increasingly standardised information and procedures, which large manufacturers are readily able to provide, there is a risk of creating barriers to entry for reused components if these requirements cannot be met.

Procurement and awareness raising

The competitive nature and fragmented supply chains of the construction industry were felt by participants in Adams et al. (2017) to provide a difficult context for new practices. Hemström et al. (2012) agree that commonly used building contracts impede reuse – though neither paper explains the mechanisms at work behind these problems. Hemström et al. suggest that more projects should adopt partnering contracts, which encourage cooperative approaches, openness and trust between parties. This form of procurement is felt to offer more opportunities to overcome practical, logistical and legal obstacles to reuse. Both studies suggest that green public procurement could provide valuable stimulus by triggering reuse activities. This was given especially strong support by the architect respondents to the survey by Adams et al.. Public construction projects and projects on public land could be required to include some degree of reuse, perhaps through use of a database system such as proposed by Hemström et al.. It is hoped that this would generate best practice exemplar projects to demonstrate the principle to wider industry, and give reuse enterprises the opportunity to establish a foothold (Hemström et al., 2012). It could create the conditions for private investment in substantial reverse logistics and reuse infrastructure. A programme such as this could be a platform for the awareness campaigns highlighted by both these studies as an important enabler. Hemström et al. also refer to training of architects and other designers in relation to the aesthetic appeal (or otherwise) of reused materials. By raising resource efficiency up the agenda on designers' education, there is a hope that their creative response could change the current public perception of secondary materials as sub-standard.

The picture of a route forward that emerges from the two studies is of greater cooperation between stakeholders as well as support from governments through public procurement and policy initiatives. An ongoing search for practical and scalable forms of reuse is seen as a role for academia. To turn these into feasible supply chains, technology may be harnessed to link separate reuse actors into a network and create flows of information through a virtual marketplace. A clear business case for undertaking reverse logistics and reuse activity is essential: this was ranked the most important enabler by all stakeholders (Adams et al., 2017). The minimal extent of reuse activity at present suggests that the case for commercial viability is either unclear, unfavourable, or both. Adams et al. call for a 'clear economic case [...] supported by metrics, tools and guidance' but do not propose what kind of context would lead to better business prospects. This is the crux of the problem, and without addressing it, metrics, tools and guidance are likely to go unheeded.

The case of structural steel

Attempts to navigate the challenges of reuse may need to explore specific material groups, so that their unique characteristics can be investigated. Moving on from the studies by Adams et al. (2017) and Hemström et al. (2012), a growing literature has focused on the reuse of structural steel. Steel presents a good opportunity for reuse, thanks to its ubiquity, durability, the significant environmental benefits that would arise from shortcutting recycling, and the intuitive feasibility of deconstructing and reusing relatively high-value steel components.

The literature reviewed here, identifies barriers and constraints; looks at cases of successful reuse to determine whether barriers are real or perceived; finds the economic case marginal; and proposes systemic and technical interventions to encourage a more effective supply chain (Allwood et al., 2012; Cooper and Allwood, 2012; Densley Tingley et al., 2017; Drewniok et al., 2017; Dunant et al., 2018, 2017; Fujita and Iwata, 2008; Geyer and Jackson, 2004; Gorgolewski et al., 2006; Ness et al., 2015; Pongiglione and Calderini, 2014; Swift et al., 2015). An interesting finding emerged from surveying and interviewing practitioners from across the supply chain who had worked on building projects involving steel reuse (Dunant et al., 2017). Reuse of steel was judged to be more expensive, slower and more difficult than using new steel, even by those who had first-hand experience of reuse being successfully carried out more quickly and at lower cost than new steel. The respondents appear to reflect general scepticism rather than their own experience, which Dunant et al. (2017) attribute to a lack of communication between supply chain actors. Greater trust and communication may be brought about by a willing client and a tightly integrated team (Gorgolewski et al., 2006), a simpler supply chain, early involvement of steel fabricators (who are found to face the most salient barriers; Dunant et al., 2017), or perhaps by the introduction of a sector-wide information system to improve flows of information about steel demand and availability (Densley Tingley et al., 2017; Fujita and Iwata, 2008).

Yeung (2016) sought to lower the costs of steel reuse by automating survey work. Manual measurement would be replaced with scan-to-BIM technology; using a point cloud scan of a member to establish its cross sectional area. If such a technology can be made to work at scale, producing reliable BIM information for existing building components, systems like those envisaged by Ness et al. (2015) and Swift et al. (2015) for new steel could be brought into practice for existing structures. They propose a strategy of 'dialogue between physical and digital worlds', achieved by Radio Frequency Identification (RFID) tags and BIM. This would monitor stress levels in members, keeping a record that would increase confidence of designers who might later specify their reuse. It would allow designers to check the suitability of members that are close to or at end-of-use in the local area, and import the existing component information into a BIM of their proposed project.

For a complete steel reuse process to become common (deconstruction, reconditioning, testing, supplementary transport and handling, fabrication) its cost would have to be less than the difference in price between new steel and scrap (Dunant et al., 2018). At present, in most cases, it is not. After making a detailed analysis of costs and risks in projects where procurement of reused steel was found to be cheaper than new, Dunant et al. (2018) highlight the important role that could be played by new market entrants or new collaborations. They suggest the need for specialist stockists that combine the roles of stockist and fabricator, with expertise in sourcing, reconditioning and testing of reused steel.

The cost challenges in the case of structural steel suggest that if reuse of less valuable components is to become common within the current economic context, there is a need for intermediaries that carry out processes that add significant value to waste. Research exploring value-adding possibilities beyond like-for-like reuse is presently scarce outside of the steel sector.

2.4.4 Reused material marketplaces

Visions of systemic change have tended to look for means of stimulating new markets in reused components by creating information flows between 'supply projects' and potential 'demand projects'. As early as 2003, web-based waste exchange frameworks to improve the planning of demolition (Liu et al., 2004; Pun et al., 2007, 2003; Pun and Liu, 2006) were being investigated. Around the same time, Hurley (2003) proposed a 'material recovery notes' system (extending the idea of packaging recovery notes) to aid in the trading of end-of-use building components. Chen et al. (2006) simulated an e-commerce system for the exchange of C&D waste which they termed 'Webfill'. Gorgolewski et al. (2006) investigated structural steel reuse and established a website with the goal of matching supply and demand. Fujita and Iwata (2008) designed a database and its integration with the processes of steel demolition, design and construction. Poelman (2009) articulated the criticality of extracting information from the supply side and envisaged a system of 'Supply Driven Architecture' in which reusable materials in buildings are assessed, and the information is made available to architects. Without reference to these

precedents, Ali (2012) diagnosed a similar problem and elaborated another information exchange system, a 'Virtual Repository', with GIS (geographical information system) mapping and newly-prevalent BIM as the platform to allow the comparison of materials available from demolition or stored in salvage yards against those needed in new construction. Ratman-Kłosińska (2013) proposed a 'StockExchange' for C&D waste, with an associated directory of reuse actors. Iacovidou and Purnell (2016) have described a 'typology system' to keep track of the properties of structural components through their life cycles and enable their efficient use and reuse. A current research project under the title 'Deconstruction and Recovery Information Modelling' aims to develop a tool for identifying reusable building components at end-of-life, for both new and existing buildings (Akinade et al., 2017; Looney, 2016).

It is evident that while related findings, ideas, and approaches exist, the various propositions lack a shared vocabulary and often do not successively build on previous research. They tend to be technology-focused. The fast evolution of available technologies may have contributed to a lack of successive development in this academic field and to poor implementation of what might be termed reused materials marketplaces (RMMs). The early work made advances by taking waste exchange markets online (e.g., Pun et al., 2003); then means of integrating with BIM became important (Ali, 2012; Volk et al., 2014); more recently there has been interest in the way that Internet of Things devices could be deployed to connect the physical directly to the virtual (Iacovidou et al., 2017; Ness et al., 2015). The focus on new technological solutions has, in many cases, distracted from the question of how to encourage uptake. The encouragement to use a new technology tends to imply a shift away from common practice, yet they are often not conceived within a wider framework of activities that would be necessary to challenge existing practices and thus bring about significant change.

This review concludes that despite the valuable contributions of all the authors in this field, practical implementations of RMMs have yet to provide a feasible alternative to conventional supply chains in mainstream construction. The small number of items available through UK examples of RMMs (e.g., Enviromate, n.d.; Loop, n.d.; Resource Efficient Scotland, n.d.; Salvo, n.d.; Trade Leftovers, n.d.) demonstrate their low uptake; others have become inactive. This discussion is taken up in sections 4.2.3 and 5.2.3.

The existing literature agrees on the need for better information about existing building components and RMMs for their exchange. The assumption is that this will allow contractors and demolition contractors to understand where there is demand for items they would otherwise discard, and initiate reclamation and resale.

2.4.5 Macroeconomic, policy and regulatory interventions

The seminal work of Walter Stahel, one of the key sources from which circular economy draws its principles, is focused predominantly on the enabling of new patterns of resource use through changes in economic context (Stahel, 2010, 2016, 2013, 1998, 1982). The present economic

context fails to punish the unsustainable use of energy and non-renewable resources and fails to incentivise the use of renewable labour. Services necessary to implement the various aspects of a low carbon, resource efficient circular economy – sustainable design, maintenance, upgrading, repair and reuse – are all labour-intensive, and thus expensive (Wijkman and Skånberg, 2015). Primary production, by contrast, is energy-intensive but relatively low in its use of labour. An increase in activity relating to the recirculation of goods, such as repair and reconditioning, thus corresponds to a substitution of labour for energy (Stahel, 1982); a proposal that looks ever more salient in an era of increasing automation. To achieve this change, Stahel and a growing chorus of voices from the construction sector and elsewhere call for taxation to be shifted away from labour and other renewable resources and onto extraction or consumption of non-renewable resources, generation of waste and emissions (e.g., Antosiewicz et al., 2016; Ekvall et al., 2016, 2014; Groothuis et al., 2016; Nakajima, 2000; Robèrt et al., 2002; Stahel and Clift, 2015). The European Commission (2011) targeted a major reduction of labour taxation and increase in environmental taxation by 2020, which has yet to transpire. Difficulties in implementing such changes include political constraints where a change in policy creates winners and losers, establishing cross-border agreements, and the risk of carbon-intensive industries simply moving production to outside of the tax jurisdiction (Aidt et al., 2017; Skelton and Allwood, 2017).

Cooper and Gutowski (2017) suggest that to increase reuse, policymakers should first amend existing legislation that presents disincentives. At national level, the UK charges value-added tax (VAT) on refurbishments but not on new build construction; a perverse incentive for demolition (Power, 2008). Stahel and Clift (2015) argue that VAT should not be levied on value-preserving stock management activities such as reuse, repair and remanufacture. The UK's forthcoming Resources and Waste Strategy may include 'increased rates of tax on virgin materials, coupled with tax breaks for manufacturers using recycled content in their products' (George, 2018), as recommended by the Aldersgate Group (2018).

Together with the Landfill Directive (EC, 1999) and the UK Landfill Tax, the WFD has succeeded in overcoming the damaging practice of indiscriminately landfilling C&D waste, as was common in the UK in mid- to late-twentieth century (BioRegional and Salvo, 2010). There is now a need for refinement of the construction industry targets to incentivise reuse over recycling, and recycling over downcycling. This could be in the form of stratified targets, such as 90% material recovery, 70% reuse and recycling, *and* 20% reuse by, say, 2030. As a waste prevention strategy, reuse may not register in measurements of waste treatment, since reused products may not reach licensed waste premises. The amendments to the WFD acknowledge this issue and require member states to establish indicators and a common method for reporting on the success of prevention and reuse strategies by 2019.

There are positive signposts ahead in the amendments to the WFD: it raises the prospect of introducing a) quantitative targets for reuse of products (European Commission, 2018: Article 9); b) other prevention measures such as waste reduction targets (Article 9); and c) specific

targets for the preparation for reuse and recycling of different C&D waste fractions (Article 11). The setting of targets according to specific waste fraction is another way to improve on the current blanket 70% figure. It would allow more precise incentives based on the nature of different materials, and get around the issue of non-metallic minerals overshadowing decisions on all other waste fractions due to mass. An alternative approach proposed by the waste management company SUEZ (2018) would be to transition from mass-based targets to a different metric, such as carbon-based targets: for instance by requiring a percentage of the carbon embodied in C&D waste to be 'diverted from landfill'. This would require considerable improvements in data quality and consistency, and consensus on methods. Zero Waste Scotland has been developing a carbon metric for all of Scotland's household and non-household waste (Lenaghan, 2017; Pratt and Lenaghan, 2017). The methods are not made explicit, but it appears to measure the carbon impact of waste as the full life cycle carbon of the product up to that point (which could be viewed as sunk costs; they cannot be influenced), minus a carbon credit where waste is recycled. The metric suffers from poorly defined waste categories (Pratt and Lenaghan, 2017) and a lack of granularity, but provides annual snapshots of the extent of embodied carbon discarded across the economy.

The UK Building Regulations have enforced significant reductions in operational energy of new and refurbished buildings, but are yet to address the rest of buildings' life cycle emissions, including those embodied in construction materials (Sturgis and Roberts, 2010). Embodied emissions associated with new construction represent a growing share of whole-life emissions, and now make up nearly a quarter of annual UK built environment emissions (Giesekam and Pomponi, 2017). Insufficient data and a lack of cross-industry consensus on the method of assessment have made the introduction of statutory limits unworkable, and where assessments are carried out voluntarily, data, methods and protocols are used inconsistently (De Wolf et al., 2017). The UK government's Innovation and Growth Team (BIS, 2010: 26) recommended the introduction of a requirement to conduct a whole life carbon appraisal. Recently this has been met by the Royal Institution of Chartered Surveyors (RICS), which published a professional statement on whole life carbon assessment (Papakosta and Sturgis, 2017). The statement makes it a requirement for RICS members to carry out whole life carbon assessment for sub-structure, super-structure and cladding materials that covers at least the materials and construction process (A1-5 in BS EN 15978; BSI, 2011) and operational energy and water use. Additionally members are to assess all other building elements and life cycle stages, unless there is a reason why this is not possible or appropriate. Harmonising the interpretation and implementation of BS EN 15978 is intended to create consistent measurement of projects' performance, so that, once sufficient data has been gathered, it will be possible to agree benchmarks for whole life carbon. This in turn will allow targets for carbon reductions to be introduced in planning requirements, building rating schemes like BREEAM, contractual obligations and the Building Regulations (Papakosta and Sturgis, 2017). Over the forthcoming years this should incentivise and then enforce the adoption of low carbon materials, including reused components.

2.5 Repurposing, upcycling, and the assessment of waste management options

2.5.1 The need for repurposing and upcycling

Many of the barriers discussed in section 2.4.1 relating to reclaimed components as physical objects hinge on their ability to be reused for the same purpose. Fitness for purpose can be demonstrated if a component has previously served the same purpose in another building. Yet if requirements have changed in the time since a component's original production, it may be obsolete for that purpose. There may be practical issues concerning the physical condition of reclaimed components that constrain direct reuse. Initiatives that aim to bring about more reuse of components that are subject to such constraints flounder on the WFD definition: only minor improvements to make components more useable are allowed. To move beyond these limitations, there is a need for imagination to be applied to the question of how secondary components could be used. Upcycling is usually understood to be a process that enhances the value or quality of a material (Kay, 1994; Sung, 2015). Thinking about repurposing and upcycling can reveal opportunities to upgrade components or use them for a different purpose, and, critically, add monetary value to reclaimed materials. This is, however, an open-ended form of investigation: if use is not restricted to components' original purpose, then how does a researcher decide where to look for new uses? Such an investigation takes steps into the unknown, in common with design, and has been embraced more by architects than by the engineering community.

Individual instances of enterprises developing new upcycling processes using C&D waste have been reported by the architects Duncan Baker-Brown (2017) and Søren Nielsen (2016), and there are examples of building projects that include repurposed and upcycled elements (Baker-Brown, 2016). Nielsen explores a vision of urban infrastructure for secondary material sorting, reusing and upcycling. The report into their design and prototype construction gives a detailed illustration of the thinking that values materials as possessing qualities even when deemed obsolete, and seeks to capitalise on these qualities. They bring to life the image of a system which does so. However, their work stops short of interrogating mechanisms for bringing the system into being and focuses instead on individual material cases. Sieffert et al. (2014) report on a practical workshop in which architecture and civil engineering students worked together to design and construct temporary buildings using repurposed and upcycled C&D waste. One project used short lengths of discarded timber to form roof trusses: an example of combining apparently unusable small pieces to perform a relatively demanding duty. These examples are rare and, when implemented, it is in niches separate from 'normal' markets (Geels, 2002). There is little research on the conditions that might generate many more such innovations or bring their perceived benefits to bear on the mainstream construction industry.

Mungkung et al (2015) propose a carbon footprint certification scheme based on the principle of upcycling: 'avoided GHG emissions of upcycled materials or products shall be higher than their

life cycle GHG emissions'. This is not sector-specific but is an attempt to use a quantitative carbon accounting method to recognise qualitative improvements to waste from any origin. Unfortunately, the case they use to demonstrate the workings of the scheme rests on assumptions that do not hold true in a European context. The case is a glass tile made from bottles, which are ground to pellets and fired at 900°C for four hours. Although their calculations indicate that the avoided emissions of producing the same tile with primary resources outweigh the production of the 'upcycled' product, their assumptions are dubious. Firstly, that the discarded bottles would otherwise be landfilled; and secondly, that a glass tile would otherwise be made from primary resources, and their product displaces this primary production on a one to one basis.

2.5.2 Life cycle assessment for waste management decisions

Life cycle assessment (LCA) is a method that attempts rigorous comparison of the environmental impacts of, for instance, the choice of material to perform a function. It can also be used to assess waste management options (Bovea and Powell, 2016; Butera et al., 2015; Clift et al., 2000; Heijungs and Guinée, 2007). The common functional unit used to compare different options is a specified quantity of a particular waste. Assessing the impacts of the waste management process itself tells only part of the story; the indirect impacts of material or energy output may override direct impacts of the waste processing (Ekvall et al., 2007). Glass recycled back into glass may avoid the production of new glass, whereas glass downcycled for use in road surfacing can only avoid the production of sand. For waste management assessment, it is therefore important to credit different options for the 'avoided burdens' they achieve outside the system boundary. Consequential LCA achieves this through 'system expansion' (Ekvall and Weidema, 2004). However, this method assumes that a secondary product directly displaces a primary product on a one to one basis, which cannot be assumed in real market conditions (Cooper and Gutowski, 2017; Geyer et al., 2015; Zink et al., 2014). Cause and effect are unlikely to be so direct; displacement is often subject to an effect similar to the so-called rebound effect in energy efficiency, where greater efficiency leads to greater consumption.

LCA may be presented as a definitive comparison of a set of options, but a lack of objectivity around the selection and relative weighting of environmental impacts leaves the reliability of LCAs open to debate (Clift et al., 2000; Van Ewijk and Stegemann, 2016). By applying six different LCA models developed by research organisations, industry associations and governmental institutions to a waste management assessment, Winkler and Bilitewski (2007) found high variation in results and sometimes inconsistent conclusions. Looking at LCA of building projects, Moncaster et al. (2018) show that differences in a) life cycle stages included, b) embodied carbon coefficients selected from databases, and c) building elements included in the scope of the assessment, can lead to very different outcomes. In their case study, any of the common structural materials under assessment could appear preferable to other options, if

calculations are limited and poorly defined (Moncaster et al., 2018). It is therefore important to reflect on findings, test the sensitivity of different assumptions as much as time allows, and present all the decisions and assumptions clearly for interrogation.

The necessity to impose a system boundary is an inherent limitation of LCA: to make calculations operable in an open system, a line must be drawn to define what will be assessed and knock-on effects that will be excluded (Bovea and Powell, 2016; Ekvall and Weidema, 2004). Even so, the quantities of data required to carry out a thorough LCA make it a time-consuming and unwieldy method.

2.5.3 'Impact reduction potential' applied to C&D waste management decisions

Geyer et al. (2015) suggest that an assessment of the quality of a recycling process must take into account (a) the difference between the impacts of the secondary processing and the impacts of the functionally equivalent primary material that it displaces, and (b) the potential for that displacement to be realised in practice. If the displacement does not occur, the recycling process can help to grow the economy, but does not reduce net demand for primary production or net environmental impacts. A waste management process with a large difference between secondary and primary production impacts, and a large potential to displace, has what Geyer et al. (2015) term high 'impact reduction potential'.

Measuring 'impact reduction potential' still relies on LCA methods. In a study comparing the refurbishment of a smartphone to its repurposing as an in-car parking permit device, Zink et al. (2014) demonstrate the importance of displacement potential. The avoided burdens of a primary smartphone's production are greater than that of a parking permit device, but the refurbished phone can only be expected to achieve a 5% displacement rate, whereas repurposing as a simple device that is not subject to fashion and regular upgrades means that primary parking permit devices are expected to be displaced on a one to one basis. They establish that under most studied scenarios and in most impact categories, repurposing is the better option. Both the intensity of avoided impacts (*what* is displaced) and the level of displacement (*how much* displacement occurs) are key to the end-of-use decision. The creative step of adapting the phone to serve a different purpose is crucial; Zink et al. (2014) conclude that repurposing allows freedom to target secondary use opportunities with high displacement potential.

Based on the elaboration of LCA by Geyer et al. (2015) and Zink et al. (2014), some broad observations can be made about the ways in which different C&D waste management options from the waste hierarchy and those proposed in this thesis will tend to perform under each criterion of 'impact reduction potential' (Table 7).

Table 7: C&D waste management options, their general tendencies under the criteria of ‘impact reduction potential’ (Geyer et al., 2015).

Activity	Typical secondary processing	Typical primary production to be displaced	Typical displacement potential ^a
Reuse	Negligible processing; transport likely to be local	Equivalent to original	Low/none – often impractical or non-compliant
Repurposing	Minimal processing including some adaptation/ additions; transport likely to be local	Sometimes greater than original, sometimes lesser, depending on use	May be low – depends on use and client appetite
Upcycling	Retain integrity of materials but undergo significant transformation; transport likely to be local/regional	Greater than original	Medium/high – varies case by case but aim for certification and constant availability
Recycling	Separate materials, break down, feed into new production; transport likely to be national/ international	Almost equivalent to original	High – established products
Downcycling	Separate materials, break down, feed into new production; transport likely to be national/ international	Less than original	High – established products

^a As the recycled materials have established demand, their displacement potential is likely to be greater than that of reuse, repurposing or upcycling. Displacement potential in the construction industry is predominantly a matter of market readiness and competitiveness, rather than the effect of secondary materials creating additional total demand, since buildings are usually only procured when they are absolutely needed. An exception would be decorative reclaimed finishes that are not needed for any functional purpose, and may be subject to changes in taste (N.B. Zink et al., 2016).

Reuse by definition has low secondary processing impacts and displaces primary production equivalent to the reused object. Its drawback is low displacement potential, owing to the barriers discussed in section 2.4.1. Repurposing and upcycling aim to improve upon this displacement potential by allowing the secondary processing to diverge from the narrow definition of reuse. Repurposing challenges the need to ‘use again for the same purpose for which it was conceived’; upcycling challenges the need to ‘use again for the same purpose’ as well as the restriction to ‘checking, cleaning or repairing [...] without any other pre-processing’.

Any of the options could be preferable in a given situation; transport alone could sway the assessment in favour of one option or another (Ghisellini et al., 2017). Table 8 provides an indicative example of each waste management activity, based on the functional unit of one reclaimed timber-framed, single-glazed window. The net impacts of the waste management activity can be expressed as the incurred environmental impacts of end-of-use processing, E_{sec} , minus the avoided impacts of primary production E_{prim} multiplied by displacement rate D (Zink et al., 2014). A low figure for $E_{\text{sec}} - D \cdot E_{\text{prim}}$ indicates high ‘impact reduction potential’. Symbols for the hypothetical magnitude of impacts are entered for each row in Table 8 to illustrate the theoretical possibility of upcycling. The processes described are notional, and a single quantity

of symbols is used as shorthand for the full range of impact categories that would be reported separately in a real assessment.

Table 8: Indicative example of C&D waste management assessment for the use of a reclaimed window, using equation from Zink et al. (2014) (quantities of symbols are illustrative only)

Activity	Notional case: 1 no. reclaimed single-glazed timber external window	Units of secondary processing impact, E_{sec}	Units of primary production impact to be displaced, E_{prim}	Displacement rate, D	Net impacts of process = $E_{sec} - D \cdot E_{prim}$
Reuse	Used again as an external window	x	xx	◇	✓✓
Repurposing	High level clerestory window in internal partition	x	xxx	◇◇	✓✓✓
Upcycling	Glass cut and laminated into glazed block/tile; timber frames re-glazed	xxx	xxxxx	◇◇◇	✓✓✓✓
Recycling glass, downcycling timber	Glass back into glass; timber enters furniture sector as particleboard	xxxx	xx	◇◇◇◇	✓✓
Downcycling	Glass treated as civil engineering material equivalent to inert minerals; timber enters furniture sector as particleboard	xxx	x	◇◇◇◇	✓

Notes:

It is acknowledged that the values of different impact categories in LCA cannot be condensed into a single figure represented by these symbols without making a value judgement over their relative weighting.

There may be consequent changes to building design following the displacement of, say, a glazed partitioning system with the repurposed windows. In a formal assessment it would be important to consider any major changes that will always result from a displacement, and take their impacts into account. However, assessing every change will be futile, given that many will be project specific, and the calculation will grow exponentially more complex and ultimately inoperable. Boundaries to the assessment must be drawn for expediency, and these are inherently artificial (Ekvall and Weidema, 2004).

Table 8 should be read as an indicative example; it does not make any claim for the superiority of one strategy over another, but aims to explain the potential consequences of repurposing and upcycling. A repurposing process will tend to have minimal impacts compared to recycling, and may have lower net impacts if an inventive and practical idea for the component's new use can be implemented. An upcycling process may have higher impacts than reuse or recycling, but may be preferable to both due to the qualities of its output. These possibilities are overlooked by the waste hierarchy.

A further quality of secondary processing that would be a factor in a comprehensive assessment is the envisaged lifespan and end-of-life of the secondary products. In some cases it will be reasonable to assume that all options under consideration will have the same lifespan

and end-of-life treatment, and to discount these factors from the calculation. However, this will often not be the case; timber is an example in which decisions made about the waste management route under consideration in the LCA will imply significant differences in the quality of recovery process that is possible at the 'end-of-next-life'. In Table 8, the reuse, repurposing and upcycling options would allow the timber to be downcycled into particleboard at end-of-next-life, whereas the best option for timber that has already been downcycled is normally energy recovery (Goverse et al., 2001). Lifespan is important because a secondary product with a short predicted lifespan causes the expenditure of impacts on replacement more frequently than a durable product. The need for a method to capture the recurring impacts of processing and maintenance of quality through multiple life cycles has been outlined in a report to the Dutch government (Schut et al., 2015). This does not appear to have been addressed by academia, perhaps because increasing complexity makes LCA more susceptible to misuse, and makes studies less likely to be comparable (Winkler and Bilitewski, 2007).

The notion of 'impact reduction potential' guides waste management decisions towards options that should achieve greater environmental benefits. Although environmental assessment practitioners may not welcome it, 'displacement potential' is an important qualification to waste management LCA. Current practice that assumes full displacement will, in almost all cases, lead to overstated benefits of secondary processes (Zink et al., 2016). However, establishing a displacement rate requires further information in a method that is already longwinded. It is likely that the extent of reduction of primary production caused by the secondary process is unknown; in which case the displacement rate will be conjectural, introducing extra assumptions. Carrying out rigorous environmental assessments thus becomes more arduous still. The valuable lessons to be drawn from Zink et al. (2016, 2014) in the context of this thesis are the importance of targeting uses for secondary components that a) are presently fulfilled by impact-intensive primary production, and b) have high displacement potential, achieved principally by improving the technical substitutability of the secondary component. This implies that there is no fixed level of 'quality' of a repurposing or upcycling process; their merits relative to other waste management options depend in each case on the emergence of technically and economically feasible ideas that use materials resourcefully.

2.6 Summary and gaps in understanding

Reuse of existing building components has environmental and social benefits, but rarely happens in practice. Many authors working with the explicit or implicit goal of increasing levels of reuse have assessed barriers, finding many. They have proposed means of addressing them, ranging from the prosaic to the imaginative. Difficulties in using reclaimed components in new construction mean that there is little demand, and the lack of demand means that there is rarely motivation to change demolition practice to yield more reusable components. Greater reuse requires, as a minimum, the development of a functioning market and reverse logistics

infrastructure; and interventions that unlock demand from client, designers and contractors and, in so doing, stimulate supply.

The phenomena observed in the literature emerge from complex interrelationships of structures; influencing the resulting behaviour is not straightforward. Approaches to the problem that identify and attempt to solve single issues require complementary approaches that integrate them into a strategy. Research on the development of markets for reused components appears sporadically, with little successive development of new knowledge, and little practical impact. This is an area with a particular need for approaches that address its complexity in a holistic, systemic manner, and locate academic findings within the practical world of construction.

Yet the constraints on reuse may prove so intractable that a shift in legislative and economic context is needed to bring about meaningful and widespread change. Even then – with, say, regulation of embodied carbon in place, and a shift from taxation of labour to non-renewable resources – direct reuse may prove too big a change in practice for much of the industry to accept. In most construction projects, the need for confidence over both quantity and quality implies that there will have to be a physical place for component consolidation and testing, and that requires a financial margin. The economic context may change and increase the feasibility of reuse business models that encompass product testing; in certain circumstances, steel reuse already is feasible. However, by dint of there *not* being cases of this working *outside* of those circumstances, it appears that greater added value must be sought than is achieved by reuse. Repurposing and upcycling are processes that might add sufficient value to cover their costs; so that their products can be certified and supplied to construction sites with reasonable lead-in times; so that, in turn, insurers, clients, designers and contractors are willing to endorse and employ them.

The lack of nuanced C&D waste targets, and the apparent simplicity of the waste hierarchy as a decision-making framework, lead to components that are not known to be reusable being prematurely downcycled. A narrow definition of reuse may have constrained thinking: there has been a dearth of creative development of the possibilities of repurposing and upcycling. They fall outside the definition of reuse, yet may be environmentally preferable if they improve the potential to displace primary production. The review identifies the need for an understanding of the context in which repurposing and upcycling ideas may emerge, proposals of how that context can be brought about, and real examples of repurposing and upcycling to illuminate and test the theory.

3 METHODOLOGY

3.1 Overview of research design

This chapter attempts to make transparent the approach taken to the research, by outlining the researcher's ontological and epistemological beliefs and assumptions and explaining the decisions taken in the research design. Methodological decisions taken throughout the project limit and frame what it can achieve. An explicit account of the logic linking research paradigm and strategy to data collection and analysis is therefore important: it explains why other courses of action were not taken, and allows critical reflection on the merits and shortfalls of the chosen approach. A framework for assessing research quality is established at the end of this chapter, and application of the framework is reported in the conclusion (section 7.3), including reflections on how the research design could be improved. Transparent reporting of the process and the researcher's own critique are intended to aid external assessment of the methodology and the research contributions.

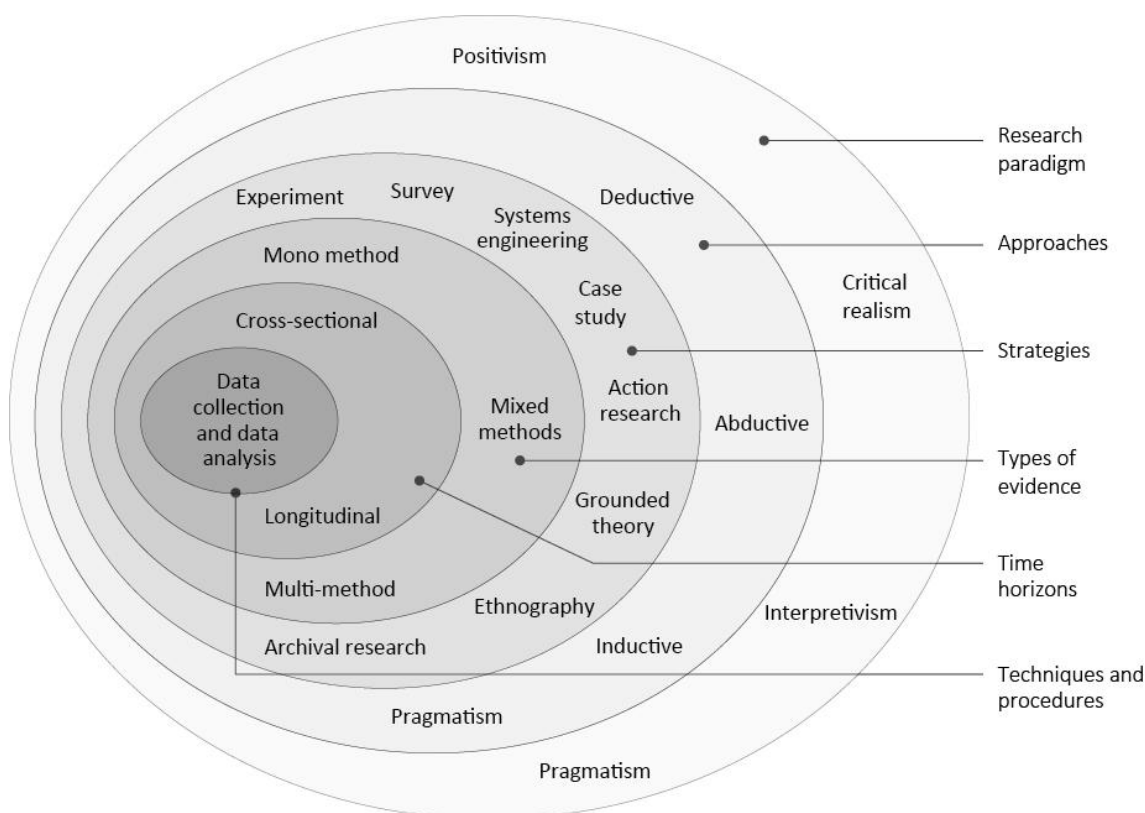


Figure 4: 'Research onion', adapted from Saunders et al. (2009) and Saunders and Tosey (2013)

Originally presented in a text book for business students (Saunders et al., 2009: 108-109), and then adapted for a general research audience (Saunders and Tosey, 2013), the 'research onion' illustrates the layers of research design (Figure 4). The outer layers provide the context for more detailed decisions made about the inner layers. Saunders et al. (2009: 124) do not dictate that one paradigm is, for instance, intrinsically attached to one approach; so although a

deductive approach may often be linked to the positivist paradigm, they caution that such 'labelling' can be misleading and may not be of any practical value. Their diagram serves as a tool for organising reflection on the various aspects of research design, and its layered structure is adopted in the following sections.

The industrial Engineering Doctorate programme is intended to place researchers in a real-world setting, with the goal that industry-based research projects will contribute to practice. The links between this research project and the industrial sponsors' operations, and the nature of the research objectives, produce the necessity to interact with, interpret and intervene in, the practice of construction. In this context, a research philosophy based around critical realism and a pragmatist approach to the generation of knowledge is set out in section 3.2; and a research strategy drawing predominantly on action research and systems engineering is described in section 3.3. Section 3.4 concerns the choice of a mixed methods qualitative and quantitative approach, the techniques for collecting and analysing data, and a commentary on researcher positionality; and section 3.5, the assessment of research quality.

3.2 Research paradigm

3.2.1 Background to research philosophies

Everyone has some form of personal perspective or philosophical belief about the nature of the world and the ways in which it is possible to understand it, even if it is rarely aired. Recognising a research paradigm within which the work has been undertaken is relevant to the thesis because it helps to make clear the systems of belief that form the researcher's 'point of departure'.

The various paradigms that underpin different philosophical positions are sometimes seen as discrete schools of thought: one is a positivist, an interpretivist, a rationalist. These positions are more like points on a spectrum than islands; few people now would locate themselves unambiguously below one of these banners (Bhaskar, 2008: 16). On a spectrum of positivist certainty to interpretivist uncertainty (Winter, 1989: 28-30), the profession of structural engineering may in many circumstances be placed towards the positivist end – it is, for instance, possible for an engineer to be fairly sure of the behaviour of materials and technology with which they design. Positivism assumes that an objective reality exists independent of social actors, and that through observation of measurable phenomena, causation can be determined and law-like generalisations established (Saunders et al., 2009: 119). To be able to make reliable measurements, positivist research seeks to create closed systems, like a laboratory experiment. However, this can only be achieved in relation to isolated aspects of the real-world context of the construction industry, which acts as an open, sociotechnical system.

Study of the use and experience of architecture may be considered much closer to the interpretivist end of the spectrum. Buildings can have meanings to people, but these are constructed by individuals in a tapestry of their past experiences, perspectives, and feelings at a particular moment in time. These interpretations are not fixed, universal or certain: they emerge from human bodies and minds that do not behave in reliable and predictable ways. The profession of architecture must engage with these human factors if it is to achieve more than simply *functional* buildings. However, unlike pure social sciences, the practice of architecture and its outcomes is not constituted solely in the minds and lives of people, like education, but is manifested in physical artefacts: the technical realisation of the built environment. Research into the use of materials in the construction industry, likewise, must address the emergence of complex behaviour involving people and organisations, but has at its core the external reality of materials, rather than constructed human relations and interpretations. In this context, critical realism is a valuable alternative paradigm in the realm between positivism and interpretivism.

3.2.2 Critical realism

Originating from Roy Bhaskar and Rom Harré in the 1970s (Danermark et al., 2005), critical realism acknowledges the subjective knowledge and influence of social actors in a given situation, as well as the existence of independent, external structures that affect the actions that these actors can pursue (Wynn and Williams, 2012). Ontologically, critical realism holds that:

1. There is a reality independent of human knowledge or our ability to perceive it. Experience by humans constitutes only a part of the real world.
2. Reality is made up of stratified domains (Figure 5): the 'Real' domain includes all structures and generative mechanisms that endure; the 'Actual' includes all events that are generated by mechanisms in the Real domain; and the 'Empirical' are those events in the Actual domain that humans experience or observe (Mingers, 2004). Therefore, epistemologically, researchers' observations of events can lead to theories about the structures and mechanisms that generated them, not as a mirror to reality but as candidate explanations that may suffer from an individual's bias, misreading and misinterpretation (Danermark et al., 2005: 10). Candidate explanations are thus fallible and socially constructed; they are never final but remain open to further debate and invalidation (Mingers, 2004; Wynn and Williams, 2012).
3. Mechanisms brought about by the power of structures in the Real domain are emergent: they evolve out of complex interactions between the entities that make up reality, including humans. As a result, mechanisms cannot be isolated in experimental conditions or explained by isolated analysis of individual entities. This makes critical realist philosophy suitable when seeking a holistic approach to the explanation of complex phenomena, such as those emerging from an open system like the construction industry.

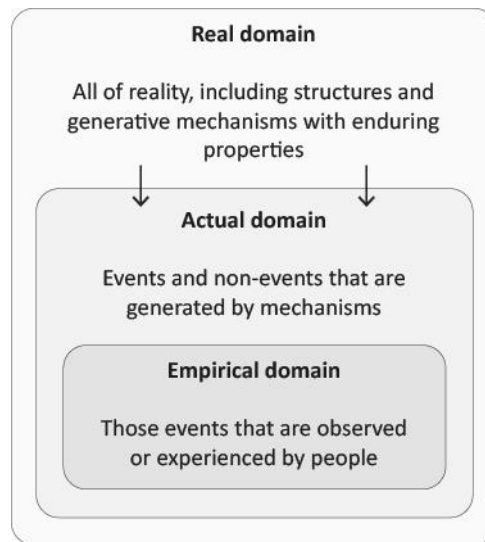


Figure 5: Critical realist ontology – the nested domains of the ‘Real’, the ‘Actual’ and the ‘Empirical’, after Mingers (2004). The term ‘mechanism’ has incongruous connotations of ‘predictable workings’, but has become a part of the critical realist vocabulary (Easton, 2010). It is therefore used in the thesis, but should not be taken literally.

4. Reality is an open and dynamic system, always in flux. Events are subject to changing contextual conditions, so causation ‘proved’ in one setting or time cannot necessarily be expected to generate the same outcomes in another. Changes through time and in different settings mean it is important always to make explicit the context in which observations are made. Critical realism focuses on explanation rather than prediction (Wynn and Williams, 2012), but thorough explanation of past events may reveal patterns of outcomes. This means that precise outcomes of, for example, proposed policies cannot be predicted; but it is possible to support policymaking by conducting well-informed discussion about potential consequences and applying judgement (Schumacher, 2010).

The goal of critical realist research is thus both more ambitious and more modest than strict positivism: it does not just measure quantifiable properties of phenomena, but has the ambition to understand their nature and question what reality must be like, what underlying mechanisms must exist, for an event to have occurred (Wynn and Williams, 2012). It is modest, though, because explanations are not ‘general laws’, but interpretations of parts of systems and their causal structures. Critical realism holds that humans have an influential role within systems, and as their behaviour, based on private consciousness alongside external factors, cannot be predicted (Schumacher, 2010), research underpinned by positivist assumptions is inadequate to explain system-wide events (Winter, 1989: 29-30).

There are likely to be multiple possible explanations of mechanisms that could have caused any observed outcomes. Not all interpretation is necessarily equal; some explanations are likely to provide better descriptions of the underlying causal structure (Mingers, 2004). Although there is no single correct answer, critical realism attempts to avoid absolute relativism; better or more

valid theories *can* be identified by ongoing observation, description and debate of ideas (Wynn and Williams, 2012). To contribute to that process, researchers must be explicit about how a particular explanation has been reached, and the ongoing collective mission of critical realist research should be to seek those that are the most useful and plausible.

3.2.3 A pragmatist approach

Approaches to the generation of knowledge are typically categorised as deductive or inductive inference. Deductive enquiry begins from a theory, generates hypotheses to be tested, and conducts tests to establish whether a hypothesis holds true under the studied conditions; then, if necessary, modifies the theory in light of findings. Inductive enquiry begins with specific observations, detects patterns within the data, forms tentative hypotheses, and works towards the development of theory. Thus theory developed inductively is a generalisation of properties found in empirical evidence (Danermark et al., 2005: 89); it is the same type of knowledge. The system of beliefs in critical realism is held to imply a different mode of inference: retroductive, or abductive, enquiry (Wynn and Williams, 2012). Attempts to understand what underlying mechanisms must exist for an event to have occurred do not rely on inference from empirical data. Abductive inference may begin with observation of phenomena, but proceed through intuition and creative thought to conceive new accounts of how events may be related to structures (Danermark et al., 2005: 88-95; Reichertz, 2010). Deductive inference can prove that something in the Empirical domain *must be* a certain way, while abduction contributes to knowledge by invoking arguments of how structures in the Real domain *might be* for events in the Actual and Empirical domains to have occurred.

Abduction can thus lead to more novel and far-reaching, albeit qualified, findings. It is seen as complementary to induction and deduction (Tashakkori et al., 1998); the three approaches can be used in combination to balance their respective strengths and weaknesses, and are appropriate during different stages of a research project. Engineering is applied research, and applying research to a world construed as complex and dynamic, in the multi-disciplinary and practical context of construction, calls for an approach that is not dogmatic but sensitive to research needs. Since few research questions are answered neatly using only one process of enquiry, Saunders et al. (2009: 127) emphasise the need for flexibility in approach. A pragmatist mindset was adopted in this project, treating each stage of research as deserving of a tailored approach (Saunders et al., 2009: 109). Thus the research approach and units of analysis vary, and were chosen based on suitability for addressing particular research objectives and likelihood of contributing to the wider project goal (Tashakkori et al., 1998: 26, 30).

In broad terms, Chapters 4 and 5 lead inductively from specific and detailed cases to theory about the existing context of construction waste management, and then proceed abductively to develop notions of how the context could be different and what interventions could create change. Chapter 6 deductively tests these theories in one material group, to verify and validate

the interventions proposed in the earlier chapters. The empirical research thus focuses on two main units of analysis: systems for the recirculation of building components at city-scale, and a specific notional enterprise operating within the urban systems. Beneath that broad framework, the execution of the enquiry created findings on each level that informed the other: the process has been iterative and generated new perspectives by the flicking of focus between urban- and product-scale systems. Table 9 sets out the overall research design and locates these approaches in the three core chapters of the thesis.

Table 9: Research design diagram for core chapters

		Chapter 4	Chapter 5	Chapter 6
Aims	Research objectives	<i>Describe what happens to building components at end-of-use; explain why the construction industry relies on waste management; and propose how a system of component management would differ.</i>	<i>Investigate how information about 'existing buildings as material banks' is obtained; propose means of improving information flows to support component management; and test how this could facilitate the emergence of reuse, repurposing and upcycling ideas.</i>	<i>Investigate the environmental implications of using secondary timber as feedstock for CLT; test the fabrication and mechanical properties of cross-laminated secondary timber (CLST); and discuss the practical feasibility and economic drivers of a CLST enterprise.</i>
	Purpose	Description and explanation	Description and change	Change and evaluation
Paradigm	Critical realist domain	Empirical -> Real	Real -> Empirical	Real -> Empirical
	Approach	Inductive, abductive	Abductive	Abductive, deductive
Strategy	Unit of analysis and scale	End-of-use material management processes Building projects -> urban Urban -> building projects		End-of-use timber management Material -> organisation
	Action research cycle	Observation, reflection, planning	Planning, action, observation, reflection	Planning, action, observation, reflection
	Methodological choice	Predominantly qualitative	Predominantly qualitative <i>selection of data drawing on grounded theory</i>	Qualitative and quantitative
Data collection	Case studies	Multiple new build and refurbishment projects	Multiple tests of triage process	CLST supra-case
	Data gathering and analysis	Semi-structured interviews, direct observation, site visits, document analysis	Site visits, photographic inventories, workshop-oriented live projects, practical live projects	Factory visits, proof of concept study, experiment, finite element modelling, process analysis, pilot manufacture

There is a risk to research quality in attempting to implement complete and repeated iterations of the research process. Doctoral research sometimes avoids this risk by focusing more closely on a single stage (e.g., theory development or empirical observation and explanation); however, given the systemic nature of the problem, it was recognised that there is a need for holistic approaches (section 2.4). It was thus anticipated that addressing the breadth of the research topic would bring greater benefit than pursuing a narrow focus.

The following sections provide a commentary on the research strategy and data collection methods summarised in the lower lines of Table 9.

3.3 Research strategy

3.3.1 Action research

The iterative approach taken in the project is analogous with the cyclic pattern of action research. In action research, initial *reflection* on a problem is developed into *planning*, which must, from a critical realist perspective, emerge from a concept of how the planned action would affect the studied structures and mechanism of the world. At this stage, the plan might be naïve, but putting it into *action* creates the opportunity for empirical *observation* and assessment of its effects. These observations can be followed by more informed reflection, which in turn can refine the plan (Figure 6).

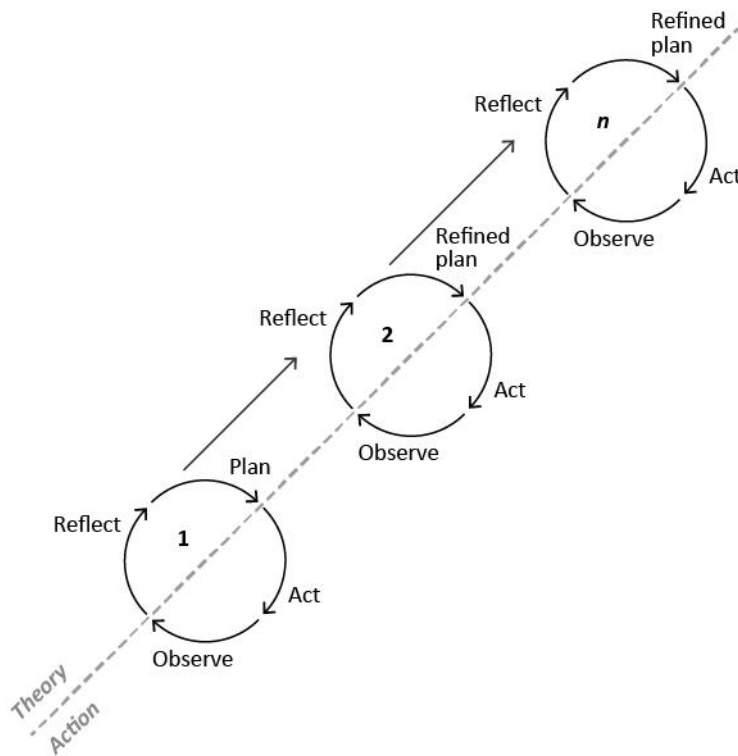


Figure 6: Action research cycle, after Zuber-Skerritt (2001)

This action research process should be understood as an 'orientation to inquiry rather than as a methodology' (Reason and McArdle, 2004). It has evolved out of the work of C. S. Peirce, John Dewey and Kurt Lewin (Barton et al., 2009), and has been transformed and applied in many different guises; its definition is not static or absolute (Altrichter et al., 2002; Zuber-Skerritt, 2001). The terminology and the way that the sequence of activities are gathered under different headings vary between authors, but in principle, action researchers advocate learning by doing (Winter, 1989). Ideas and hypotheses are tested by 'change experiments', preferably in the context that they aim to influence (Barton et al., 2009). The researcher is involved in the subject of study, rather than attempting to act as a neutral bystander, free of values (Perry and Zuber-Skerritt, 1992). There is often a social motivation to an action research strategy, in which

'researchers work with and for people', co-producing knowledge, 'as opposed to simply undertaking research about them' (Fahy and Davies, 2007). Reason and Bradbury (2001) emphasise the 'pursuit of practical solutions to issues of pressing concern to people'. These moral aspects may be shaped by social scientists' suspicion of research into people's behaviour that is produced exclusively in academic institutions, at a distance from their subjects (and in a dominantly positivist paradigm) (Reason and McArdle, 2004). Such researchers' goal is for power to be shared between researcher and active participants, rather than held tightly in the hands of the academic.

Since Lewin's (1946) seminal paper introduced the term 'action research' as a means of investigating intergroup social relations, action research has been used in graduate management research (Perry and Zuber-Skerritt, 1992), intra-company problem solving (Zuber-Skerritt, 2001), design practice (Swann, 2002) and in many other fields (Kemmis et al., 2013: 4). There are some examples in waste research: Fahy and Davies (2007) and Farrelly and Tucker (2014) use action research in addressing household waste minimisation. They note that household waste behaviour has been investigated primarily through quantitative methods, and adopt action research approaches to (a) add depth and nuance to knowledge of waste behaviour, and (b) encourage individuals to take up pro-environmental behaviour, on the basis that providing people with information alone is often ineffective. A similar approach could be envisaged in C&D waste management, collaborating with individual construction workers to understand behaviour and encourage waste minimisation and segregation. However, this may struggle to achieve widespread impact due to structural impediments beyond the individual's control. In a conference paper reporting on the early stages of an action research project on urban C&D waste management systems, Aid and Brandt (2010) note the conflict between an individual's agency and large-scale system change. Their project participants proposed a multi-stakeholder process to catalyse change, but unfortunately any subsequent outcomes of this strategy have not been published.

The present project look for ways to improve practice, so it adopts a strategy inspired by the action research connection of practice and theory; but it recognises the limitations of working with individuals on complex systemic problems. Various aspects of the work were carried out with the involvement of practitioners. However, unlike action research undertaken in purer social science settings, the primary intention of this engagement was not to bring about immediate change within an organisation or group of people. The emphasis, instead, was on learning about practice, by oscillating between action and reflection to develop increasingly thorough descriptions of structures, mechanisms and possible interventions (Acaroglu, 2014: 8-9). The goal is to describe a context for wider, longer-term change, outside the scope of the research project; that is, more on the 'research' than the 'action' (Dick, 1995, cited in Swann, 2002). Towards this end, action research provided, firstly, a process of learning from the way that individual organisations relate to the context and issues of C&D waste management; and

secondly, of investigating how they might relate to proposed interventions. In so doing, it leads to suggestions of how a context for change could be conceived and implemented.

3.3.2 Systems thinking and systems engineering

Frequent reference is made in the thesis to ‘systems’. Systems are understood as cohesive sets of interacting elements, in the line of thinking advanced by Ludwig von Bertalanffy (1968) in biology; but they can be natural or human-made. Depending on the lens through which they are considered, systems can be seen at various scales. A system may be decomposed into a collection of sub-systems, and may in turn be integrated within a higher-level system (INCOSE, 2017). To say that something behaves like a system is not to claim that it can be reduced to this depiction, or deny its interactions with other elements outside of the imposed system boundary (Checkland, 1983). Systems thinking emphasises the complex interactions between systems, and emergent behaviour from these multi-scalar entities (Flood, 2010). This is analogous to the structures and generative mechanisms that produce patterns of behaviour in critical realist analysis. A critical realist paradigm and systems thinking both encourage non-reductionist exploration of the complexity and multi-disciplinarity of open systems (Easton, 2010; Flood, 2010; INCOSE, 2017). Positivist research, by contrast, must create artificially closed systems to achieve the conditions necessary for deductive inference (Barton et al., 2009).

Given the indivisible and indefinite nature of an open systems view of the world, every piece of research requires some demarcation of a boundary around the studied phenomena. In systems thinking, the researcher’s judgement is called upon to define what really comprises a phenomenon and what is relevant in its context (Winter, 1989: 47-48). The related field of systems engineering provided useful tools for organising thought on the demarcation of the urban- and product-systems studied in this project. Systems engineering begins from a problem statement and a set of requirements to be met by the system design (INCOSE, 2017). Although systems engineers are often concerned with ‘hard’ systems (where a boundary and system requirements can be more definitively expressed, e.g., a piece of software to meet a company’s needs or a transport system to meet urban needs), the model proposed by Martin (2004) is not specific to any one discipline, and its flexibility makes it applicable to this project. His ‘seven samurai’ model (Figure 7) proposes a means of considering all aspects of system requirements holistically, to minimise the risk of misconceiving needs and aim at reaching the ‘best’ solution to the problem. The ‘intervention system’ is the primary system to be designed, but modelling the six connected systems attempts to ensure the design’s effectiveness in the given context as well as successful adaptation to a changing context.

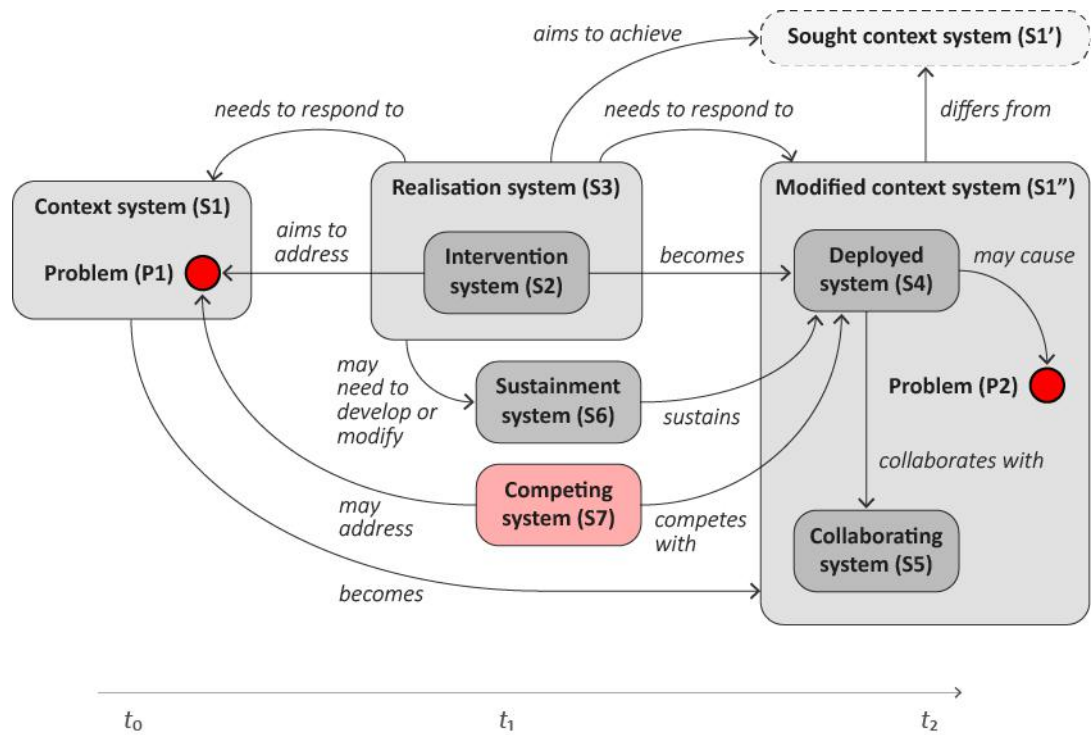


Figure 7: 'Seven samurai' systems engineering model, holistic view, adapted from Martin (2004)

The design of an intervention begins with an understanding of the context system (S1), within which is the identified problem (P1). To bring the intervention system (S2) to bear on the problem requires a realisation system (S3), which consists of all the tangible and intangible resources needed to conceive, develop, produce, test and deploy the intervention. Martin (2012) gives an example: the problem of needing to transport people over long distances, addressed by the intervention of the passenger jet, with a realisation system comprising jet engine manufacturers, airline companies, airports, safety standards, and so on. The realisation system may be in the form of an enterprise, and must be responsive to the nature of the context system.

The goal of the intervention is to solve the identified problem and thus transform the existing context system into the sought context system (S1'). When put into action, the intervention system becomes a deployed system (S4). The deployed system may differ from the design of the intervention system, and it may or may not achieve the intended changes; it may have unintended consequences that manifest as new problems (P2) in a modified context system (S1''). The context may have changed because of the passage of time, or because of its interactions with the deployed system. Martin (2004) did not distinguish between what are here termed S1' and S1'', but doing so makes the goal of the intervention explicit and contestable, and in the fullness of time, allows the gap between design intent and reality to be assessed.

In most scenarios, a deployed system will not address the problem by itself, but will have associated collaborating systems (S5) that will also interact with the context. To maintain the running of the realisation system requires a sustainment system (S6), the limitations of which

could undermine the running of the deployed system if not considered at the outset. Finally, there may be competing systems (S7) that aim to solve the same problem in a different way, and may conflict with the deployed system. By highlighting the interactions between all of these systems, Martin's model aims to stimulate systems engineers who focus 'too much [...] on the intervention system' to acknowledge the complex, adaptive nature of their work (Martin, 2012). The model is intended to ensure that the systems engineering process is verified ('building the right system') and validated ('building the system right').

In adopting this framework, it is necessary to qualify its use. In Martin's work there is an implicit belief that a problem's context is knowable and that a systems engineer will be able to diagnose needs and respond with 'correct' decisions, i.e., that they can grasp the structures and generative mechanisms that lead to observable phenomena and react objectively and impartially. In this project, the fallibility of perception and interpretation is acknowledged. However, the pragmatist approach to the study accepts Martin's tool as an effective means to an end: it presents boundaries within which to formulate ideas about an existing and envisaged context, and to describe the various facets of interventions intended to engender a transition.

In summary, action research provided a guiding strategy for the sequences of research activity, and systems engineering provided a strategy for conceptualising the outcomes of this activity and formulating interventions. Both strategies are connected to design processes in their iterations of activity between concept and detail, between thought and action, and between analysis of how things 'are' and how they 'ought to be' (Hevner et al., 2004). Designers' knowledge can be said to be primarily of the artificial world – the human-made world of artefacts, and changes or additions to it (Cross, 2001) – this is different to knowledge of the natural world. The normative is more inherent in the artificial; the question of how things ought to be cannot be avoided or considered outside the designer's remit, and the designer cannot remain a detached observer. The author's experience as a designer-practitioner implies a 'designerly' way of knowing, and a strategy that begins from, and cyclically returns to, a normative vision of a modified construction industry context. The research strategy thus cycles between description of problems within an existing context (observation and reflection), proposal of alternative scenarios in which problems are solved (planning), and provisional testing of intervention and realisation systems needed to achieve the change (action and observation).

3.4 Data collection and analysis

3.4.1 Types of evidence: mixed methods

The starting point for the collection and analysis of data was immersion in the subject. Exposure to many sources of potentially valuable data can benefit abductive interpretation of

phenomena by permitting a situation to be viewed from multiple perspectives. Although the methods of classical grounded theory (Corbin and Strauss, 1990; Glaser and Strauss, 1967) were not stringently followed, the research process drew from grounded theory the notion that 'all is data' (Glaser, 2002) and simultaneous data collection and analysis (Charmaz, 2006: 23-24). The process had more in common with Charmaz's (2006) 'constructivist grounded theory' than what she calls 'objectivist grounded theory' (i.e., following the mould of Glaser, Corbin and Strauss), in its acceptance of the researcher as an involved agent within the research topic. The researcher acted as participant-observer engaged in the topic of material reuse and upcycling through several roles, besides purely working towards the accomplishment of the academic thesis, both prior to and during the project: initially as an architecture student, then an amateur artist-maker, a practising architect, an architectural tutor, a director of Remakery Brixton Ltd (RBL; a reuse-focused workplace start-up), a supervisor of MSc and MRes research projects, a hands-on agent in reuse activity connected to the industrial sponsors, and a potential entrepreneur exploring an upcycling business model spinning out of the research.

A criticism of the involved qualitative researcher is that knowledge generation will be subject to the individual's perceptual limitations and pre-conceived biases. Others argue that subjectivity cannot be ruled out in any research (Barton et al., 2009; Flyvbjerg, 2011: 309-311; McKeown, 1999). All research, however conceived, is the work of individuals, who decide what they will research, where they will and will not focus attention, and who cannot avoid drawing to some extent on their past experience and knowledge. Humans more readily recognise evidence that verifies their pre-existing interpretations: 'It is the peculiar and perpetual error of the human understanding to be more moved and excited by affirmatives than negatives' (Bacon, 1873, quoted in Flyvbjerg, 2011: 309). Bias or subjectivity cannot be eliminated, but it can be managed, for instance through transparent acknowledgement of the researcher's background and any normative aspects of the research; through attempts to recognise assumptions that may have been made; and through triangulation of different types of evidence gathered from a number of sources (Denzin, 2009; Yin, 2014).

Past experience that the researcher brought to this project is set out in the top rows of Table 10 and discussed in section 3.4.4. Greater neutrality was sought through co-production of knowledge with practitioners and other researchers (Green et al., 2010), and through the use of qualitative and quantitative data (Firestone, 1987; Saunders et al., 2009: 153) to provide triangulation. Bazeley (1999) borrows Denzin and Lincoln's description of the researcher as a '*bricoleur*, piecing together emergent solutions to a puzzle'. In that spirit, the intention has been to triangulate between different methods to build confidence in findings and tackle different parts of the thesis topic. Physical places of production, practitioners, regulations, and materials themselves are all key facets of the topic, so the research incorporated, inter alia, visits to construction sites and factories, interviews with practitioners, assessment of waste reporting, and engagement with materials through prototypical manufacture and laboratory testing (Table 10). Many of these methods were carried out as part of case studies, used to develop

understanding of the present context, and to test responses to it. In Chapter 4 the cases involved observation of live building projects, and in Chapter 5, engagement with construction processes, both related to the operations of the industrial sponsors. In Chapter 6, several separate investigations contributed to the case of cross-laminated secondary timber (CLST).

Table 10: Researcher's past experience and forms of data gathering used during the project

Role connected to research topic	Relevant data gathering activities	Case studies or time period (key to abbreviations below)
Architecture student	Assessing discarded goods for reuse in design projects	Prior to EngD
Amateur maker/artist	Collecting discarded things, remaking practical objects, fine art objects and installations	Prior to EngD
Practising architect	Managing reclamation and reuse of components in built projects	Prior to EngD
Architectural tutor	Leading design studios focusing on reuse of buildings and components and public engagement	Prior to EngD
Director of RBL reuse workplace	Managing RBL materials storage space and workshops	Prior to EngD – September 2015
	Managing volunteers to help with storage of discarded materials and their reuse in construction	Prior to EngD – December 2014
	Hands-on voluntary construction work to upgrade premises using discarded materials	Prior to EngD – December 2014
	Project managing manufacture of café furniture and light fittings from discarded materials	July – October 2015
Industrial sponsor engagement	Participant observation – time spent in industrial sponsors' offices	PH, THH; 1-2 days/week from January 2014 – February 2018
	Participant observation – meeting attendance	AV, CSE, DH, KR, LE, FP, PH, PP
	Presentation to relevant teams within sponsors	Every 6-12 months
	Observation of C&D waste practices – visits to construction sites	AV, DH, KR, LE, RM, SPW
	Observation of C&D waste practices – visits to waste transfer stations	WM1, WM2, WM3
	Semi-structured interviews with members of client organisations, contractors and waste management companies	AV, DH, KR, LE, PH, RM, THH, WM1, WM2, WM3
	Gathering and reviewing waste reports	AV, DH, KR, RM
	Inventorying and surveying available materials	AV, SPW, KH
	Fostering exchange of materials to local projects	CH, CSE, FP, MGC, PP & others
	Workshops and collaboration with architects to explore practice in relation to real reuse opportunities	CH, CSE, FP
	Engagement with local community groups, businesses and projects	CWS, Kafe 1788, Parklet, PP
	Hands-on reclamation of materials and remaking	CSE, PP, SPW
	Meeting local authority to influence area masterplan	PRHZ
Core doctoral researcher role	Gathering and reviewing existing and new literature	See Appendix G
	Presenting at academic conferences and workshops	See Appendices C, D, E and F

Role connected to research topic	Relevant data gathering activities	Case studies or time period (key to abbreviations below)
Core doctoral researcher role (continued)	Attending invited industry/policy workshops, seminar discussion groups and public lectures and events	See Appendix H
	Informal conversation and correspondence, involvement in related discussions with academics and members of the public	Throughout
	Observing news in engineered timber through CLT LinkedIn group	CLST; January 2015 – September 2017
Co-supervisor of Collaborative Environmental Systems Project	Engagement between five Master’s students and RBL to design systems for reuse workplace logistics	October 2013 – April 2014
Co-supervisor of MSc projects	Evi Unubreme: fabrication of CLST specimens and lab testing; review of CLT LCAs	CLST; May – September 2015; see Appendix I-1
	Tianyao Lyu: fabrication of CLST specimens and lab testing; overcoming barriers to CLST production	CLST; May – September 2015; see Appendix I-2
	Yushi Li: video explaining the extent of C&D waste and intervention ideas; survey of the video’s effect on viewers	May – September 2015; see Appendix I-3
	Crystalbale Tiu: removing contaminants from secondary timber and processing CLST	CLST; May – September 2016 see Appendix I-4
	Thibault Dufresne: FEM of CLST	CLST; May – September 2017 see Appendix I-5
	Xing Zou: LCA of CLT and CLST	CLST; May – September 2017 see Appendix I-6
Co-supervisor of MRes project	Structured collaboration on existing stocks of secondary timber – extensive survey and calculations	CLST; November 2015 – May 2018
	Observation of reverse logistics operations – visit to timber reuse enterprise	CLST; see Appendix J-1
	Observation of timber waste practices – visit to timber grading and recycling plant	CLST; see Appendix J-2
	Survey of buildings and components across housing zone	PRHZ; see Appendix K
Potential upcycling entrepreneur	Observation of CLT fabrication process – visit to Stora Enso CLT factory, Austria	CLST; Appendix J-3
	Hands-on processing of secondary timber and fabrication of CLST as pilot project	CSE, CLST
	Taking modules at UCL and London Business School on new venture development	CLST
	Pitching business opportunity to potential funders	CLST; see Appendix H
	Presenting innovation to public as part of Victoria & Albert Museum <i>Friday Late</i>	CLST; see Appendix L
	Developing EPSRC research proposal to continue CLST research	CLST; ongoing

Abbreviations: AV = Aberfeldy Village; CH = Commonweal Housing; CLST = cross-laminated secondary timber; CLT = cross-laminated timber; CSE = Chrisp Street Exchange; CWS = City Wood Services; DH = Decent Homes; FP = Fashioning Poplar; KH = Keys House/Dorset House; KR = Knapp Road; LCA = life cycle assessment; LE = Leopold Estate; MGC = Mobile Garden City; PP = Poplar Pavilion; PRHZ = Poplar Riverside Housing Zone; RBL = Remakery Brixton Ltd; RM = responsive maintenance contractor; SPW = St Paul’s Way; WMx = waste management company number x

3.4.2 Case studies

Case studies are recognised as an effective method for exploring complex issues and bringing out rich and detailed understandings of events in their real-life setting (Dobson, 2001; Yin, 2014). Barrett and Sutrisna (2009) make this argument in the specific context of research into construction projects. Connecting case study research to the critical realist paradigm, Easton (2010) characterises case studies as ‘investigating one or a small number of social entities or situations about which data are collected using multiple sources of data and developing a holistic description through an iterative research process’.

In deductive research with a positivistic approach, proving or disproving a hypothesis is carried out on the basis of statistical probability, and so there is a need for a large enough sample size to merit confidence in the claim. Research with a critical realist perspective, by contrast, builds up a description from empirical evidence, then seeks to interpret the likely mechanisms at play that led to the observable evidence. The interpretation is of a particular context leading to particular phenomena; the critical realist appreciates that this context is not static, and therefore that their interpretation is limited to its time and place. Although the results of this approach may be enriched by investigating a number of cases, it relies on no more than one (Easton, 2010; Flyvbjerg, 2011: 304-305).

The period of case study data collection based on projects relating to the industrial sponsors ran from January 2014 to December 2017. During this time the researcher was formally affiliated with the sponsors and sought out suitable projects to analyse as case studies, for a) observation, description and explanation of existing context, between January 2014 and December 2016; and b) testing proposed means to bring about recirculation of building components, between October 2015 and December 2017. Figure 8 sets out the case study projects, their timeframes, and the periods of structured data collection. Description of the Chapter 4 case study projects are included in Appendix M and detailed accounts of the methods that were applied to the case studies are included in Appendix N and the relevant parts of the thesis.

A research project can adopt a cross-sectional (‘snapshot’) or a longitudinal time horizon. Longitudinal case studies allow linkages and patterns of behaviour that might not appear in a snapshot to emerge over time (Dobson, 2001; Easton, 2010). For the study of construction activity, longitudinal data collection allows a more rounded view, as building projects take a long time to complete. Longitudinal case studies were possible in this project, up to a point. Structured data collection by way of site visits and interviews required the input of resources from contractors (i.e., organisations outside of the research team), over whom the industrial sponsors had limited control. In practice, therefore, it was not possible to make regular site visits over the course of entire projects. The ‘burden’ of supporting the research was instead shared between various contractors on different sites, allowing the stages of building soft strip, refurbishment, demolition and construction to be witnessed and pieced together. Where

possible, a connection was maintained to case study projects even if the period of structured data collection had ended, for instance by continuing to receive waste reports, through occasional site visits, or through discussion with members of the industrial sponsors.

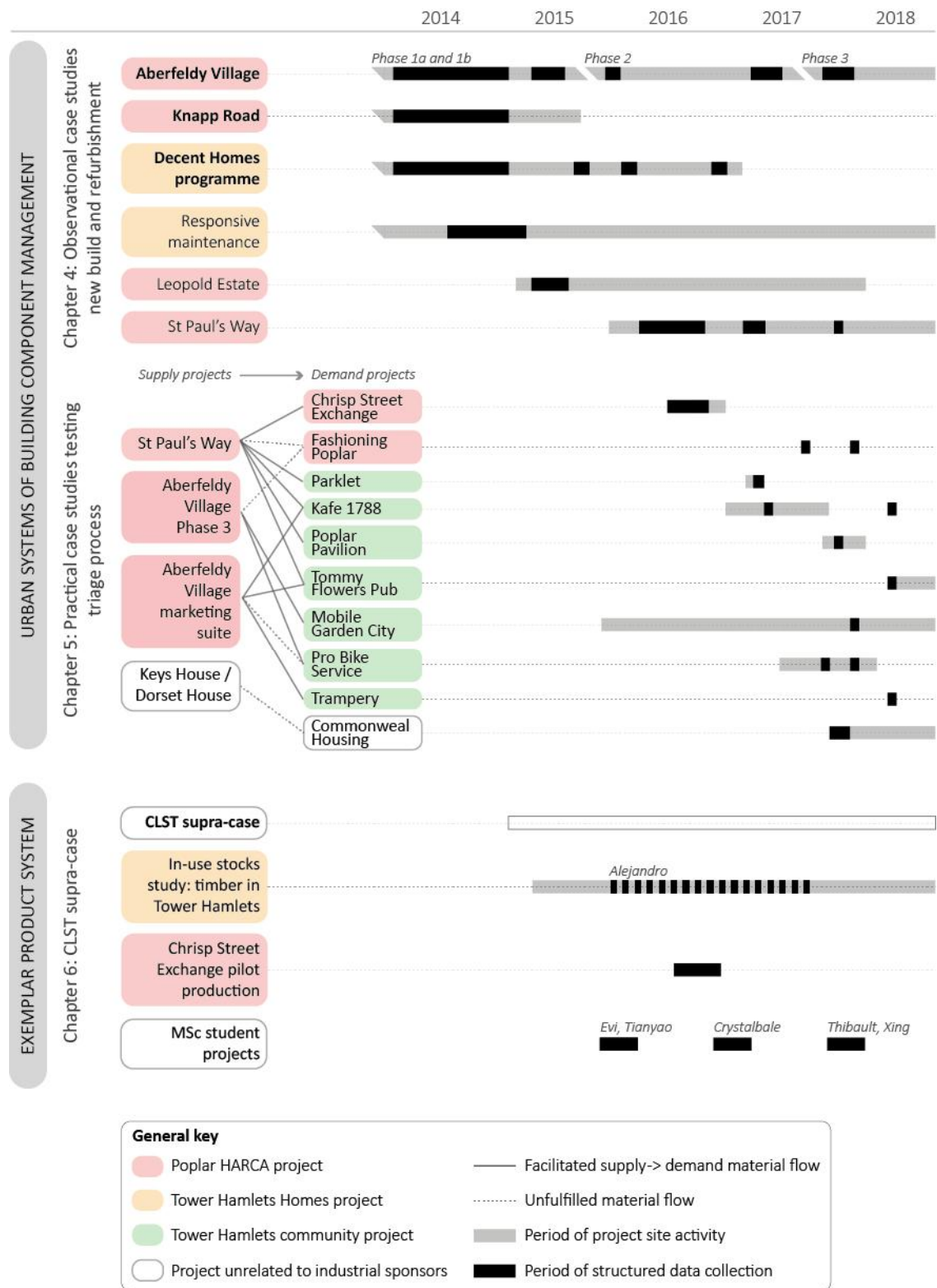


Figure 8: Timeline of case study projects indicating main periods of project related data collection

3.4.3 Data analysis

The analytical procedure common to the whole investigation was the iterative process of building understanding from gathered data and experience (reflection and planning) followed by and informing the next stages of action and observation. Within this overarching process, data generated by different methods were analysed using techniques related to 'memoing' in grounded theory. Memos are a means of condensing and restructuring data (Charmaz, 2006: 72-73; Corbin and Strauss, 1990); they provide the researcher with a key to recall earlier analyses and enable further reflection. 'Diagramming', as described by Charmaz (2006: 117-119), provides a similar tool in visual format. Describing situations, relationships or systems visually often suggests new linkages that may not emerge from prose, which, by nature, is linear. Sutrisna and Barrett (2007) establish the complementarity of visual descriptions of systems with grounded theory methods. They use 'rich picture diagrams' to analyse the richness and complexity of data collected from multiple construction project case studies (Barrett and Sutrisna, 2009).

In this project, data frequently were not textual; drawing diagrams was a critical activity throughout for re-presenting information to encourage new interpretations, and for exploring systemic links. The diagrams that remained most relevant as the research proceeded are reproduced in Appendix O. Notetaking and extensive rewriting of notes was also used throughout the project to process thoughts and condense important points. The application Evernote provided a simple way to collect notes into thematic groups or subjects, edit and search. Models and conceptual frameworks developing out of diagrams and notes were refined through continual re-expression in different formats (Saunders et al., 2009: 484). This helped to identify what the next step in the research should be as much as it helped to reflect on the significance of past steps.

Relevant methods of analysis were applied to individual parts of the study. For example, the textual information collected from the first set of case studies was grouped into a case study database; interviewees' testimony was coded; later in the project, some quantitative analysis was used as part of the CLST case study, such as finite element modelling. Details of how these methods of analysis were used can be found in the relevant parts of the thesis.

3.4.4 Researcher positionality

Typically EngD projects are conceived by industrial sponsors with a view to their application in the organisation's practices. In this case, the project was self-initiated by the researcher, and the housing sector sponsors came on board later. They brought a keen interest in the topic, but no specific intention for *how* the project's findings might be applied across their London borough, or in their operations. The lack of a definitive agenda on the part of the sponsors, and the expectation that doctoral research will have applicability to a context beyond individual organisations, led the researcher to pursue aims that would contribute to the sustainability and

resilience of the construction industry at large. The goal of helping to shape systems from which new reuse, repurposing and upcycling ideas would emerge, beyond the timeframe of the project, is an indirect and long-term approach to the sponsors' everyday generation of C&D waste and use of building components. It is not the unequivocal solution that could perhaps have been wished for. However, there grew a shared understanding that shifting the construction industry to more circular practices is a significant challenge that would require incremental transition.

Being affiliated with the two industrial sponsors provided access to the staff managing their housing projects, to other project participants such as contractors and architects, to project documentation, to other projects connected to the local community, and to work space and meeting rooms. Both offices had a hot desk arrangement, and sitting in different parts of the offices afforded the opportunity to overhear conversation relating to different parts of the organisations. The presence of the researcher allowed staff to raise ideas, flag up pertinent news, and discuss developments on projects relating to sustainability, waste or reuse and recycling, which might otherwise go unspoken. This type of observational data and happenstance conversation would be largely inaccessible had the research been undertaken exclusively in an academic institution.

As a former practising architect, it is likely that the researcher, almost without noticing, sifted out certain ideas, approaches and interpretations as impractical or unworthy of further attention. This is both a strength and a source of potential oversights. Someone caught up in day-to-day practice is more likely to recognise and give weight to reasons why an alternative practice will not succeed. They may be correct in exercising their detailed knowledge of the boundaries, limitations and workings of the practice to see what is feasible; but on the other hand, they may be restricted by the weight of their own knowledge. A researcher with some knowledge of a practice, but without the burden of its daily implementation, may get carried away with lofty ideas of change, blissfully unaware of the impossibility of their realisation; or, divested of other responsibilities, they may have the clarity to see today's achievable improvements – or even picture a route to a vastly altered future. These are caricatures; in reality, practitioners and researchers alike will sit within a range of practical and imaginative responses to a given challenge. What is the most effective degree of proximity to a problem? Problems that are not easily solved often require both mindsets: unburdened thinking and close attention to detail. The relationship between the two modes of thinking is likely to be more fruitful when it is iterative, in the mould of action research – not just handed down from the blue-sky thinkers to the doers – and when different participants collaborate and learn from one another.

Prior to starting the doctoral project, and alongside architectural practice, the researcher ran participatory 'co-design' projects between architecture students and various 'client' groups. These can have value in bringing to bear on students an appreciation of the responsibility of design: that it is not a paper exercise, but an embedded set of decisions with real social ramifications. Seeing students progress through projects also showed how important it is that

they can step back from the participatory activities and reappraise the work in a more detached way. With too much regard for the client group, they fail to elevate the design beyond arbitrary requests made in briefing sessions; they fail to synthesise briefing information with their own, unique view of how those needs might be elegantly met. With too little regard for the client group, their own unique view becomes detached, aloof, and sometimes opaque or even alienating to participants at the next workshop.

For the EngD, working in the pragmatic field of construction industry material management, the research position adopted begins with today's reality, and then develops and tests responses to it. The understanding of existing context is co-produced, because the breadth of knowledge of people working in construction industry material management today is essential. The response to this understanding of context, however, in the form of engineering systemic change, is like the students stepping away from the participatory work: a synthesis that blends the findings from the different strands of investigation with imagination. This is sense-checked with practitioners and tested through further stages of action and observation, but not co-produced. Practitioners are working in the present and are primarily focused on the present. The academic engineer has the luxury of not having to practice; it is their duty instead to be able to reflect on the present in order to think beyond.

3.5 Research quality

The test of 'truth' in a pragmatist approach is successful outcomes: 'analyses are true only in terms of the accomplishment of particular goals' (Hayes et al., 1988). Since this project aims to contribute to the understanding of systems for component recirculation that can, over time, change industry practices, the ultimate measure for its quality is whether such change occurs, and whether the research made a decisive contribution. Within the confines of the project timeframe, however, it has to be assessed through proxy measures such as the rigour with which the research was undertaken, and whether it made specific, relevant contributions to knowledge.

Assessment of the rigour of quantitative research is often made against the criteria of reliability and validity (Bryman, 2012: 46-50). Reliability in this sense is a quality of a measurement that causes it to produce a consistent result each time it is used, i.e., a way of measuring that can be relied upon to produce a non-fluctuating outcome. Validity has several facets, but tends to be divided into the question of whether a measurement really measures what it claims to measure ('measurement validity'), the confidence one can have in claims of causal relationships ('internal validity'), and whether findings can be generalised beyond the specific research context ('external validity'). Bryman (2012: 48) describes 'ecological validity' as the further question of whether research findings that may be technically and academically valid make sense in the context of people's everyday lives. He proposes that this can be assessed by considering

whether the instrument of data collection lifts ‘naturally’ from life, or whether it creates a level of artifice (e.g., a survey is not a way that information is naturally passed from one person to another). Guba and Lincoln (1994: 114) include objectivity, the ability of the researcher to remain a distanced and neutral observer.

There is some debate over whether and how these criteria, which in positivist research would be used with regard to quantitative measurement, can be applied to research that is predominantly qualitative. For example, in the light of the commentary on positionality and the influence that the researcher as an individual brings to critical realist research, the notions of objectivity and reliability, or repeatability, cannot truly be attained (LeCompte and Goetz, 1982). In closed-systems experimental research, the conditions for the experiment can be closely approximated to past research to test repeatability of methods and outcomes. Attempting to repeat research into open sociotechnical systems will not create the same situation because the studied context will have changed over time. The process may be repeatable, if it is capable of being adequately described, but not the outcome, or its subjective interpretation. Similarly, generalisability presents a problem to this type of research, with critical realism’s emphasis on the decisive importance of context. Research in one area may suggest structures in the Real domain that would have wider influence, but complex interactions between structures and generative mechanisms may conspire to create different events in a different context (Wynn and Williams, 2012). Thus generalisations are always fallible and subject to fresh scrutiny by the researcher who attempts to extend them to a new setting (Mahoney and Goerts, 2006).

The difficulty of applying these positivist quality criteria in interpretivist or critical realist research stems from the lack of a shared epistemological belief in researchers’ ability to learn absolute truths about the subjects they study. ‘Trustworthiness’ and ‘authenticity’ have been proposed as alternative criteria for qualitative research (Bryman, 2012: 390-3; Guba and Lincoln, 1994: 112, 114). Trustworthiness has a number of facets that mirror the quantitative criteria for research quality, while authenticity concerns the wider political impact of social sciences research that has human participants at its centre, i.e., the benefits to subjects, ethics and fairness, where *people* are the unit of analysis. However, some contend that universal measures for research quality are unhelpful, and seek more flexible and contextually situated criteria for qualitative research (Tracy, 2010). On that basis, Table 11 extracts the categories of trustworthiness and authenticity that were deemed relevant to this project, where material processes, rather than people, are the fundamental unit of analysis. These are synthesised with complementary quality criteria proposed by Hammersley (1992; cited in Bryman, 2012: 394-6), Guba and Lincoln (1994) Yardley (2000) and Tracy (2010), to develop an assessment framework appropriate to the research.

Table 11: Framework for assessing research quality (adapted from Bryman, 2012: 390-6; Guba and Lincoln, 1994; Tracy, 2010; Yardley, 2000)

Criteria	Guiding questions	Explanation
Relevance	Is the rationale behind the research made explicit, and is it compelling? Does the research question the status quo, and does it contribute to the field?	'Good qualitative research is relevant, timely, significant, interesting, or evocative [...] Research that is counterintuitive, questions taken-for-granted assumptions, or challenges well-accepted ideas is often worthwhile' (Tracy, 2010). Relevance is assessed in terms of the importance of a topic within its substantive field or the contribution it makes to the literature (Hammersley, 1992, cited in Bryman, 2012: 394-6).
Credibility	Is the adopted methodology explained in sufficient detail to allow the logic of the research design to be assessed? Is the risk of error reduced by adopting a pluralist research approach based on multiple perspectives?	A parallel to internal validity (Guba and Lincoln, 1994; Tracy, 2010). Many interpretations of given observations are possible, and one way of judging the trustworthiness of an interpretation is credibility: bias and fallibility should be minimised by good research design (Saunders et al., 2009: 156-7), including triangulation of sources; by learning from practice and presenting back to practitioners (respondent validation); by engaging a wider academic community; by presenting findings to the wider public; and by the use of rigorous procedures (e.g., a doctor, lawyer or priest does not guarantee a successful outcome, but offers an assurance that well-established principles will be carefully applied) (Winter, 1989: 36).
Transferability	Are context, methods and findings described in sufficient detail to allow future researchers to consider transferability of research to a new setting, and to carry out similar research processes?	A parallel to external validity (Guba and Lincoln, 1994); also considered an aspect of 'resonance with readers' (Tracy, 2010): rather than the researcher claiming generalisability, the study may resonate with readers, who may transfer the account to their own context. The burden of assessing whether findings in one context can be transferred to another lies with the person doing the transferring. To aid in this process the study should provide rich accounts of phenomena, and clear delineation of the time, place and setting that was researched.
Sincerity and dependability	Is the research undertaken without undue bias, and is the researcher's personal agenda acknowledged?	While objectivity is not possible, sincerity (Tracy, 2010), confirmability and dependability (Guba and Lincoln, 1994) attempt to ensure that the researcher has acted in good faith. 'Sincerity as an end goal can be achieved through self-reflexivity, vulnerability [...] it] means that the research is marked by honesty and transparency about the researcher's biases, goals, and foibles as well as about how these played a role in the methods, joys, and mistakes of the research' (Tracy, 2010).
Practical significance	Is the knowledge of use? Did methods of data collection arise naturally from the studied context, and was the development of the research shaped by practitioners, based on knowledge of industry practices?	Concept of practical significance (Tracy, 2010) encompasses 'ecological validity' (Bryman, 2012: 48), 'catalytic authenticity' and 'tactical authenticity' (stimulates and empowers action; Guba and Lincoln, 1994). Practically significant research provides impetus to engage in action that could change circumstances; addresses barriers reported elsewhere in the literature; considers the complexity of the context and proposes responses integrated with that context (rather than proposing 'solutions' to a single issue without cognisance of the wider issues facing decision makers in practice); it has 'impact and importance' for both theory and practice (Yardley, 2000).
Coherence and commitment	Do the research objectives emerge from the problem statement, and does the study plausibly accomplish its aims?	Substantial engagement with the subject matter, applying relevant skills, thorough data collection and analysis (Yardley, 2000). Coherent research addresses its stated aims using research strategies that make sense in the light of the adopted paradigm, and logically connects research objectives with existing literature, new findings and interpretations (Tracy, 2010).

3.6 Summary of the adopted methodology

This research attempts to form principled and bold perspectives on the changes needed to 'improve' end-of-life material management practices in the construction industry. In this conviction, the research strategy borrows from action research the principle of iterating between reflection and practical action; and from systems thinking and systems engineering, the tools for conceptualising and formulating interventions in complex, open systems.

The philosophical position of critical realism assumes that empirical observations are a result of generative mechanisms created by underlying structures, of which people can only ever be partially aware. To attempt effective intervention in a system, accounts of the existing context must go beyond empirical evidence and attempt to understand these structures. To that end, case studies were used throughout the project: initially to generate rich and detailed understanding of real-life context, and then, alongside abductive inference of new concepts for material management, to test those concepts in practice.

The project's collection and analysis of data draws on constructivist grounded theory, in which the researcher is an involved agent within the research topic, and in which 'all is data'. Interpretation is unavoidably influenced by the researcher's positionality as well as the particular circumstances in which evidence was gathered. This can create criticisms such as partiality and subjectivity, to which the best response is reflexivity and openness. The research project was instigated with the goal of bringing about more reuse in the construction industry, and although overly ambitious, this continues to present itself to the researcher as a valid and valuable motivation for the work.

4 URBAN-LEVEL EXISTING AND SOUGHT CONTEXT SYSTEMS: C&D WASTE MANAGEMENT AND COMPONENT MANAGEMENT

4.1 Introduction to urban-level investigation

Cities are where most existing building components are stocked; they are where there is the most turnover, of old buildings deemed obsolescent, and new development to replace or upgrade them. The study could focus at project level, but the existing literature suggests that the context in which project-level decisions are made is critical. It could focus at a national level, but the sheer size of building components means that their reuse is likely to remain local. The urban level, where there is a density of construction activity, of materials both needed and discarded, provides the most fertile context for component recirculation.

This chapter addresses the first research objective. Most of the chapter is drawn from Rose and Stegemann (2018a). The extracts from the paper build up a model of the current system of C&D waste management, developed out of analysis of the initial set of case studies: six housing regeneration projects in the London Borough of Tower Hamlets that were under construction at the start of the doctoral project. This observational stage in the research cycle fed into reflection on the structures and mechanisms that frame the decision to discard potentially reusable components. From the current model, or 'existing context system' in systems engineering parlance (Martin, 2004), the chapter goes on to describe component management as a part of the 'sought context system'. It proposes in outline form a 'triage' intervention system, and identifies responsibilities for various actors and areas of further investigation needed to enable better component management. These proposals were refined through subsequent cycles of action research before being written up for publication.

This chapter challenges the assumption that components removed from the building stock must either be directly reused (which is often impractical), or sent to waste management (which does not capitalise on the value of existing components, and wastes embodied environmental impacts). It discusses the role and implementation of repurposing and upcycling as partners to a more comprehensive test of the potential for direct reuse.

4.2 From waste management to component management

4.2.1 Methods used in the initial investigation

Multiple case study approach

The objectives were pursued through multimethod qualitative case study research conducted with two housing organisations. The research was undertaken with a critical realist perspective (Danermark et al., 2005). Six live projects were chosen as case studies: one large-scale new build (construction cost >£30 m); one small-scale new build including demolition (<£10 m); three widespread refurbishment packages including soft strip (each >£30 m); and one smaller refurbishment package (<£10 m). A background of the case study projects is provided in Appendix M.

Sources of evidence

Case study methodologies encourage the triangulation of sources of evidence to increase internal validation of data and accuracy of observations (Denzin, 2009). The scientific method was organised around three main sources of evidence (Yin, 2014) reported in the three subsections of 4.2.2:

1. fieldwork observations on construction sites and through regular visits to the waste transfer stations (WTSs) used in the case study projects;
2. documentation, which was largely in the form of contractors' SWMPs and waste reports; and
3. in-depth semi-structured interviews with 21 interviewees from the contractors, waste management companies, and members of the two client organisations (Table 12). Although an interview length of at least 60 min was sought for in-depth investigation (McCracken, 1988), the average length was 48 min.

Data analysis

Raw data from interviews collated in a case study database were coded under emergent themes. Interviewees' testimonies on each theme were compared and contrasted, leading to the identification of a series of commonly reported issues and their possible underlying drivers (Table 30, Appendix P). These were analysed in the context of the literature review and other sources of evidence, in order to form explanations for the current situation (section 4.2.3). Lastly, a systems engineering approach (based on Martin, 2004) was adopted in the development of an intervention in response to the findings. Further explanation of the methods of data collection and analysis used in the case studies is supplied in Appendix N.

Table 12: Summary of interviewees.¹

Company type	Role	No. of interviewees	Background/expertise
Contractor	Project director	1	Construction management, business development
Contractor	Contracts manager	4	Contracts management, building trades
Contractor	Senior site manager	1	Construction management, building trades
Contractor	Sustainability manager	3	Sustainability, consultancy
Contractor	Health, safety and environment manager	3	Health and safety, administration, sustainability
Waste management	Operations manager	3	Waste logistics, haulage
Waste management	Sales manager	1	Waste logistics, sales, public relations
Client	Project director	5	Construction management, project management

¹ Limitations: interviews with individuals unavoidably contain a degree of subjectivity and a risk of biased viewpoints or inaccurate reporting of events. These limitations were mitigated by carrying out interviews with several people from each case study project. Across different projects and with interviewees occupying different construction industry roles, the same topics were covered, increasing confidence in the testimony.

4.2.2 Case study findings

Fieldwork observations of C&D waste logistics

A picture of the steps by which C&D waste is currently managed was built up based on direct observations in the field:

All case study projects except one employed a skip service. Typically, there is inadequate space on site to have different skips for each waste stream, except for the compulsory segregation of hazardous and non-hazardous waste, and metals that are generally separated at source and sold as scrap due to their value. The weighing of incoming skips and separation of waste fractions is undertaken at the WTS through a series of heavy plant operations, trommel screening, and manual sorting. The WTSs were all within 25 km of the construction sites.

WTSs are places of huge throughflow: waste carriers' vehicles will typically arrive every 2-5 minutes. The operation only works, spatially and economically, if waste is continuously pushed through the system and out again, on the back of another truck, on to its next destination. Time and safety concerns prevent any manual sifting of reusable components from taking place, and, in any case, the sheer ruggedness of the environment means that good materials are unlikely to avoid damage.

Different waste fractions separated at the WTS travel to different destinations as their capacities and gate fees change, but haulage is a major cost so waste management companies seek to

avoid large travel distances. In this study, the next destinations of waste fractions were within 75 km of the WTS. In the case of recyclables, these destinations were generally only the next link in a long chain of businesses involved in turning unwanted construction components into raw materials, for manufacture into a product with recycled content. This chain can extend to other parts of the UK, Europe, and – for metals, some plastics, and some cardboard packaging – worldwide.

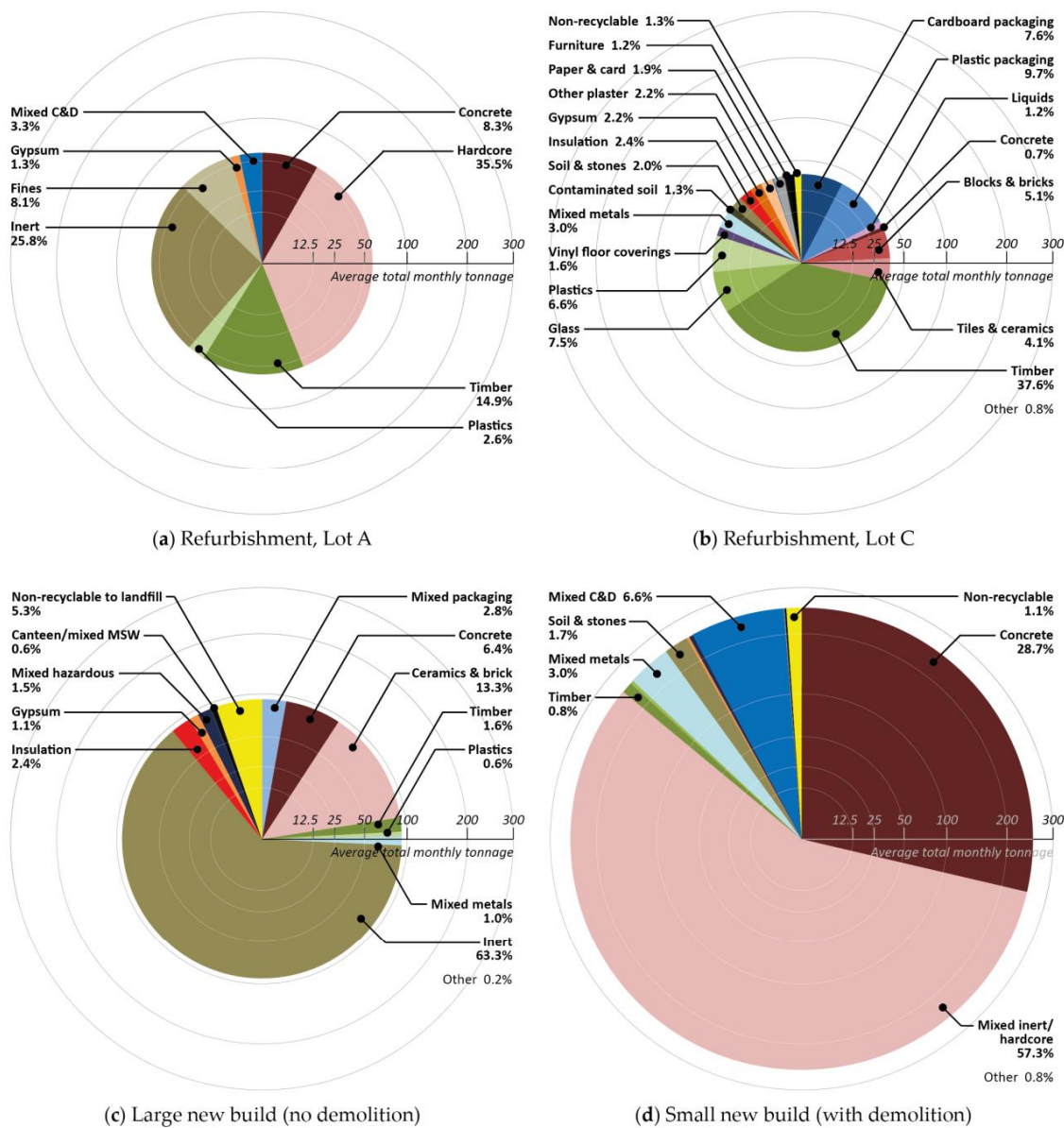
A more detailed description of the logistics of C&D waste management observed in the case study projects is provided in Appendix Q.

Documentation and reporting of C&D waste

Although the UK's legislative requirement to carry out SWMPs has been repealed, in all cases the contractual arrangements between contractor and client continued to require them to be completed. However, the requirement to report on waste is typically fulfilled after-the-event by waste management companies. None of the contractors in the study collected their own data on quantities and types of waste arising, which is consistent with usual practice in this sector. None had carried out a pre-redevelopment audit (NFDC/IDE, 2016) of materials that would emerge as waste from demolition and soft strip.

Waste is categorised by waste management companies based on European Waste Catalogue (EWC; European Commission, 2000) codes, corresponding to the waste fractions that the company transfer away from the WTS (Figure 9). Waste management companies report back to their customers based on a record of the total quantity of each material processed at the plant. Typically, they assume that the waste profile of any given skip matches the profile of everything processed at the WTS (e.g., Figure 9a). Unless waste is segregated at the source, they are usually unable to report the actual quantities of each waste fraction received from any given project or contractor. Only one waste management company made visual assessments of skips' contents at the moment of tipping, to estimate by volume the proportion of different wastes received (Figure 9b). Some companies report only a total tonnage of 'mixed C&D waste' (EWC code 17 09 04). Thus, it can be seen that the information is retrospective; rarely specific to actual project or actual materials; classified into coarse categories; and directed at the contractor and client of the source project (rather than at any potential new users of the materials).

Combining all case study projects, a total of almost 95% of waste was reported as sent to recycling industries (Table 13), although the data do not account for the proportion of waste actually recycled downstream.



Key	Material	EWC code	Negligible quantities greyed out	
	Oils	13 01 13*	Glass	17 02 02
	Cardboard packaging	15 01 01	Plastics	17 02 03
	Plastic packaging	15 01 02	Vinyl floor coverings	17 03
	Mixed packaging	15 01 06	Mixed metals	17 04 07
	Liquids	16 10 02	Contaminated soils	17 05 03*
	Concrete	17 01 01	Soils and stones	17 05 04
	Bricks and blocks	17 01 02	Fines	17 05 04
	Tiles and ceramics	17 01 03	Insulation	17 06 04
	Mixed inert/hardcore	17 01 07	Gypsum	17 08 02
	Timber	17 02 01	Other plaster/cement	17 08 02
			Mixed hazardous	17 09 03*
			Mixed C&D/'roof waste'	17 09 04
			Paper/cardboard	20 01 01
			Soft floor coverings	20 01 11
			Paint	20 01 28
			Electrical (MSW)	20 01 36
			Vegetation	20 02 01
			Canteen/mixed MSW	20 03 01
			Bulky/furniture	20 03 07
			Non recyclable	

Figure 9: Waste stream breakdowns for case study projects, as reported by waste management companies. Waste categories and names are used inconsistently by different companies; the colours shown are based on the EWC codes they used, translated into our key, and the labels are as stated in their reports. Charts (a) and (b) relate to waste from two contractors doing the same type of refurbishment work, aggregated over several months. One would expect the breakdowns to look similar. The data in (a) come from an estimate based on the overall WTS figures; in (b), from an estimate carried out visually on a skip-by-skip basis. Therefore (a) is modelled on the waste from a far larger sample size – it should represent a more generalised profile of C&D waste streams in London – whereas (b) should be a more accurate model of the project in question.

Table 13: Total proportions of each waste stream and treatment method for all case study projects.

Treatment	Waste stream	Breakdown by weight	Total by treatment method
Reuse	n/a	0.0%	0.0%
Recycling	Mixed packaging	2.7%	
	Concrete	19.3%	
	Mixed brick, tiles, hardcore	41.9%	
	Timber	5.8%	
	Glass	0.7%	
	Plastics	1.2%	
	Metals	2.3%	
	Soil and stones	18.8%	
	Insulation	0.7%	
	Gypsum	0.9%	
	Mixed C&D	0.4%	94.5%
Recovery	Timber	0.2%	
	Mixed C&D	0.8%	
	Undefined	0.7%	1.7%
Landfill	Mixed C&D	2.7%	
	Undefined	1.1%	3.8%
Total			100%

Interview findings

The purpose of the interview process was to examine the roles and practices that frame the decision to reclaim and reuse or discard components to waste management. Attitudes and perceived constraints expressed in interviews are described by topic in Table 30 (column 3) in Appendix P. These are interpreted in light of the authors' fieldwork observations (column 4), and underlying barrier and driver mechanisms and their causes are suggested (columns 5 and 6).

The client organisations in the case study projects did not instruct the reclamation of components from soft strip or demolition for reuse on site, so it was left to contractors to decide whether to deconstruct or demolish. Interviewees reported time, cost, and health and safety implications to deconstruction; the commercial benefits of resale were not apparent to them. Anecdotally, successful demolition contractors are very careful to identify components that they can reclaim and sell, as this represents their competitive advantage. However, in the case study projects – decommissioning of mid- to late-twentieth century housing and soft strip of elements within it for upgrading – demand for the components being produced was considered unlikely. The salvage industry was treated as a proxy for all market demand, and little emerges that would normally be seen in a salvage yard.

In this context, the assumption that components have no further use remains untested. The contractor lacks knowledge of needs beyond their current project and is not motivated or equipped to make a robust assessment of component usefulness. Their role does not normally involve product supply, and the idea that items they discard could be transformed for some new purpose did not occur in interviews without prompting. The use of RMMs to test demand and

sell reclaimed components is not established practice. Those interviewees that were aware of their existence reported finding them inconvenient (time-consuming with low expectation of sales) or untrustworthy (typically selling to unknown and uncontrollable individuals rather than to businesses). Interviewees could not imagine their own company using RMMs to purchase materials, due to non-compliance with client specifications, concerns over quality, and concerns over quantities available. Given that they do not perceive major consumers of building materials like themselves as potential customers, their scepticism about posting items to RMMs is logical. To do so is considered a positive, community-minded action, but not a viable alternative to conventional waste management. The skip service, by contrast, is simple, familiar, and reliable. Even though skip removal is perceived as expensive, gate fees are not so high as to incentivise widespread investment in alternatives.

Two people at different waste management companies felt that the amount of good quality timber and plywood they see coming through their yards would, in their words, 'make you weep'. Indeed, a normative idea arose in several interviews, that those materials that can, should be used. This appeared to be a primary motivating factor for those contractors who had in the past found ways of passing on useful materials to the benefit of others, rather than any saving in disposal costs, or boost to their company's corporate social responsibility. Frequently, the default behaviour is to discard without considering reusability, but, in some cases, contractors' willingness to seek out alternatives is apparent. On those occasions, their intentions were often frustrated by the lack of a mechanism for bringing reuse connections to bear.

4.2.3 Discussion of existing context and sought context

'Where we are': systemic mechanisms leading to components being discarded as waste

Drawing on the three sources of evidence, the system of waste management observed in the case study projects is illustrated geographically and logistically in Figure 10, and findings are synthesised in the following discussion.

There is a mature infrastructure underpinning the chains of recycling and energy recovery mapped in Figure 10; the economic value of feedstocks is understood through the network and fees payable by contractors and waste management companies are reasonably predictable. By comparison, the case study projects exhibited no examples of reuse and little connection to the salvage industry or any other reuse infrastructure. This absence makes it difficult to evaluate whether reclamation will be cost-effective. Discarding components to waste management is perceived as a safe, default position that was unchallenged in all case study projects (Figure 11a). This perception that components are unwanted and valueless sets in motion a series of steps from which it is difficult to recover any component performance. Components are treated as a liability rather than an asset, undergoing destructive demolition rather than careful dismantling. Contractors do not see value in creating the capacity to take a proactive role in

sorting and redistributing these materials: instead, the skip service provides a simple release valve. Once discarded to a skip, they are 'waste', subject to further damage and mixed with other wastes. WTSs provide the interface with the rest of the waste management infrastructure, but are not set up as places for reclamation. By the time waste has reached the WTS, therefore, the management options are effectively limited to recycling, incineration with or without energy recovery, and landfill.

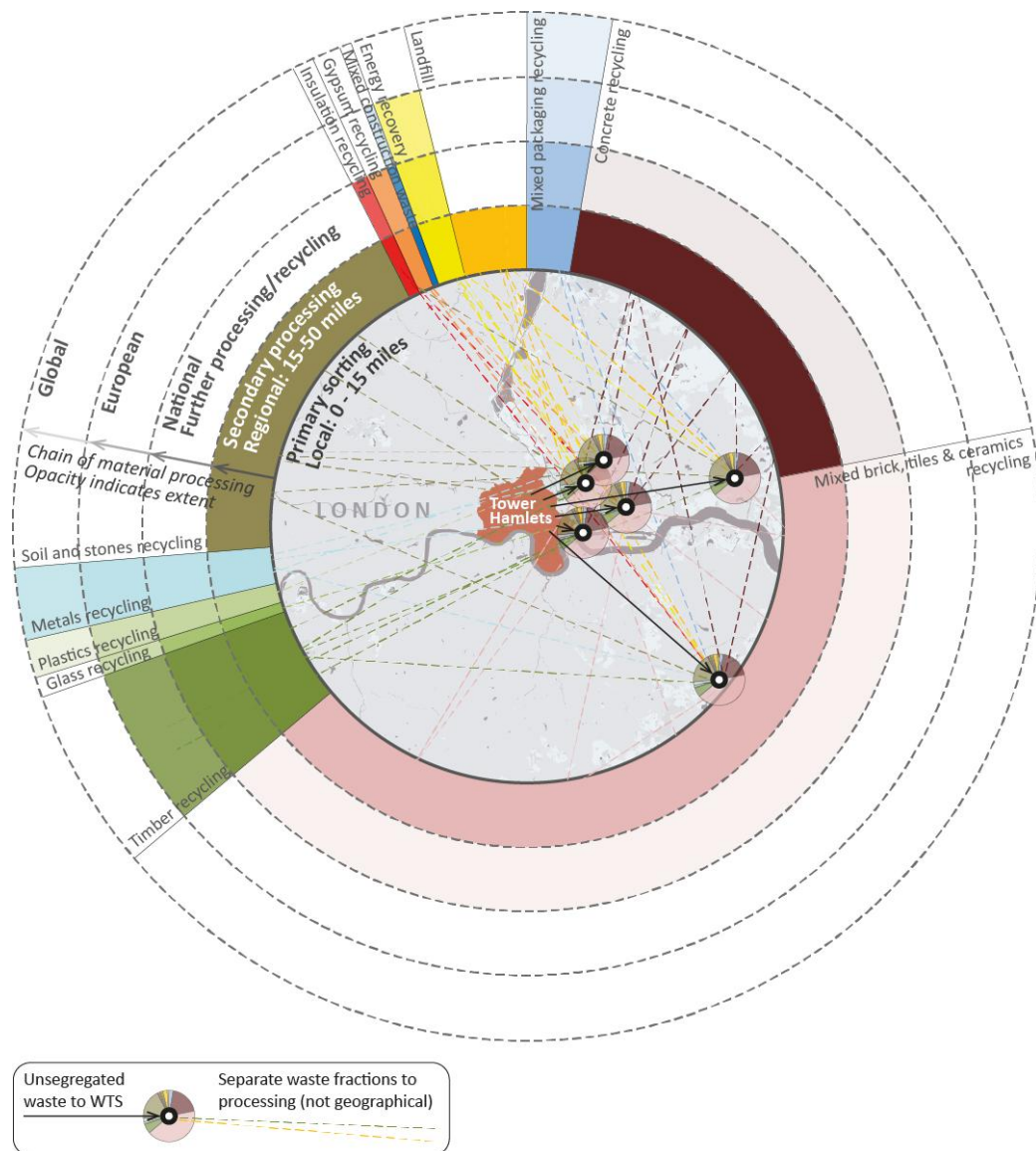


Figure 10: Diagram illustrating existing waste management logistics from case study projects. The map in the centre shows the area of London from which unsegregated site waste originated and the locations of waste transfer stations (WTSs). Arrows indicate the transfer of waste from construction sites to WTSs, and their links to onward waste processing. In the rings outside the map, the angle formed within a sector indicates the material's proportion of total waste reported across all case study projects, and the opacity of the sector in each ring indicates the geographical extent of the material's processing. Thus, the metal sector reaches as far as the outer ring at almost full opacity, because the majority of metal recycling happens beyond Europe.

If building components are to be reclaimed, demand must be recognised from the outset. To establish whether there is demand requires timely and appropriate information about existing building components. Nascent systems of component management are illustrated in Figure 11b,c, in which an audit provides the starting point. This could be in the form of a pre-redevelopment audit, or informal identification of reusable components, such as the practical knowledge that a demolition contractor may apply when tendering a job.

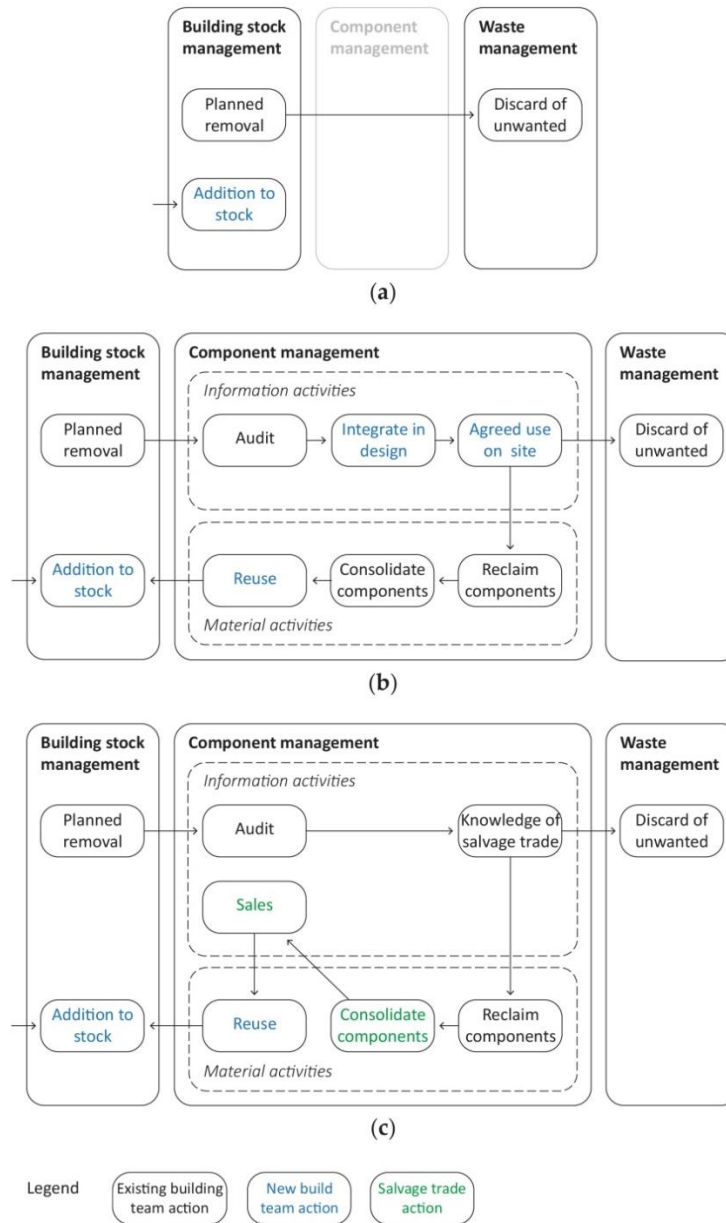


Figure 11: Current scenarios for the sequence of activities that determine treatment of existing building components: (a) no consideration of potential to retain component function – complete reliance on waste management, as seen in the case study projects; (b) nascent component management – formal or informal audit and engagement of new build team, allowing potential for some secondary use on site, as reported, e.g., in BioRegional (2011); (c) nascent component management – formal or informal audit and knowledge of salvage traders, leading to some reuse off site. Combined use of (b,c) represents current best case scenario, with continued reliance on waste management for the majority of components removed from stock.

The primary source of information about materials emerging from the case study projects was waste reporting. As well as being generated too late in the process, these reports do not provide a qualitative understanding of components that would be necessary in identifying demand. EWC codes or the categories of the European Waste Statistics Directive (EWC-Stat; European Commission, 2002) capture all types of waste, but do so in a way that is geared towards waste management, rather than component performance, despite the intention of aiding waste prevention. Taking an example, there are only two EWC codes for timber construction waste: 17 02 01 (wood), and 17 02 04* (glass, plastic, and wood containing or contaminated with dangerous substances). The codes do not distinguish between a solid timber joist, a kitchen unit of particleboard and melamine, and a panelled door: distinctions that would need to be drawn in order to understand whether such components can serve others' needs. The point is demonstrated by Figure 12a: a 'soil and stone' pile with large blocks of cut granite in amongst soil and gravel. All are '17 05 04' as far as the EWC is concerned, and all attract the lower UK landfill tax rate for inert waste, but are very different in terms of embodied carbon, performance, and value. Measuring in terms of undifferentiated tonnage or volume of broad waste categories biases their disposal towards downcycling en masse.

A detailed understanding of specific building components is not necessary for them to serve as feedstock for conventional recycling, because they will be returned to the state of raw material. This loss of specificity means that recycling can provide certainty over future (albeit lower) usefulness (Densley Tingley et al., 2017). The usefulness of a specific reclaimed component, with its idiosyncrasies, is far less clear-cut. Individuals from the contractor and the design team will have an intimate awareness only of the needs of their current project, or a handful of projects in which their company is involved. Thus, there is a vantage point problem in the scenarios illustrated in Figure 11b,c: those faced with deciding components' fates do not have the vantage point to see other projects that might be able to use them. This interpretation is consistent with reports in the literature: the proportion of components successfully reclaimed and reused remains low, even in the best case of thorough auditing (BioRegional, 2011; Carris, 2011).

RMMs hold promise in addressing the vantage point by creating a flow of information between supply and demand. This study suggests that the limited uptake of RMMs is down to three main weaknesses. Firstly, items are usually offered at the time that they arise as waste, and this does not leave a period for architects and engineers to incorporate particular components into design development, or for buyers and sellers to negotiate a deal. Secondly, since most contractors do not consider using RMMs to post unwanted items, very little tends to be available. Thirdly, items may be offered without the warranties required by insurers (McGinley, 2015), so although UK Building Regulations have a fitness for purpose clause that should facilitate the appropriate use of reclaimed materials, they are viewed with caution in mainstream construction (BioRegional and Salvo, 2010). Without sufficiently early information, adequate choice, and assurance over the quantity and quality of offerings, the ability to capitalise on

RMMs is limited to small and informal demand projects that are less selective and can make immediate use of materials.

Given the vantage point problem and the limitations of RMMs, direct reuse connections often do not materialise. The waste hierarchy indicates that recycling (in any form) then becomes the preferred option, validating conventional waste management (Van Ewijk and Stegemann, 2016). This could be seen as premature. The current system (a) does not allow the potential for direct reuse to be explored systematically, and (b) does not identify scope for remanufacturing and upcycling. These processes are potentially more practicable than reuse and environmentally preferable to downcycling, but are not supported by the waste hierarchy. The following section attempts to embed a thorough exploration of reuse and the overlooked possibility of upcycling into a system of component management.



Figure 12: Waste transfer stations, (a) soil and stone pile (European Waste Catalogue (EWC) code 17 05 04): inadequacy of codes in differentiating performance; (b) tipping: good materials unlikely to avoid damage.

‘Where we want to be’: a triage process to support reuse, repurposing, and upcycling

Based on an analysis of C&D waste management processes, the previous section explained that for building components to be reclaimed, demand must exist and be identified from the outset; that to serve latent demand, specific components’ qualities as well as quantities must be identified; and that to overcome the vantage point problem, this information must flow between supply and demand. It was noted, however, that the demand projects that can directly reuse components identified in this way are limited. For demolition practices to change (and thus increase the supply of reclaimed goods), there must be timely evidence of demand at scale. This section expands on the nascent model of component management illustrated in Figure 11 to address the identified needs and shortfalls. It describes a series of interlinked activities that are necessary to form a triage process (Figure 13) in pursuit of the aim of more comprehensive component management.

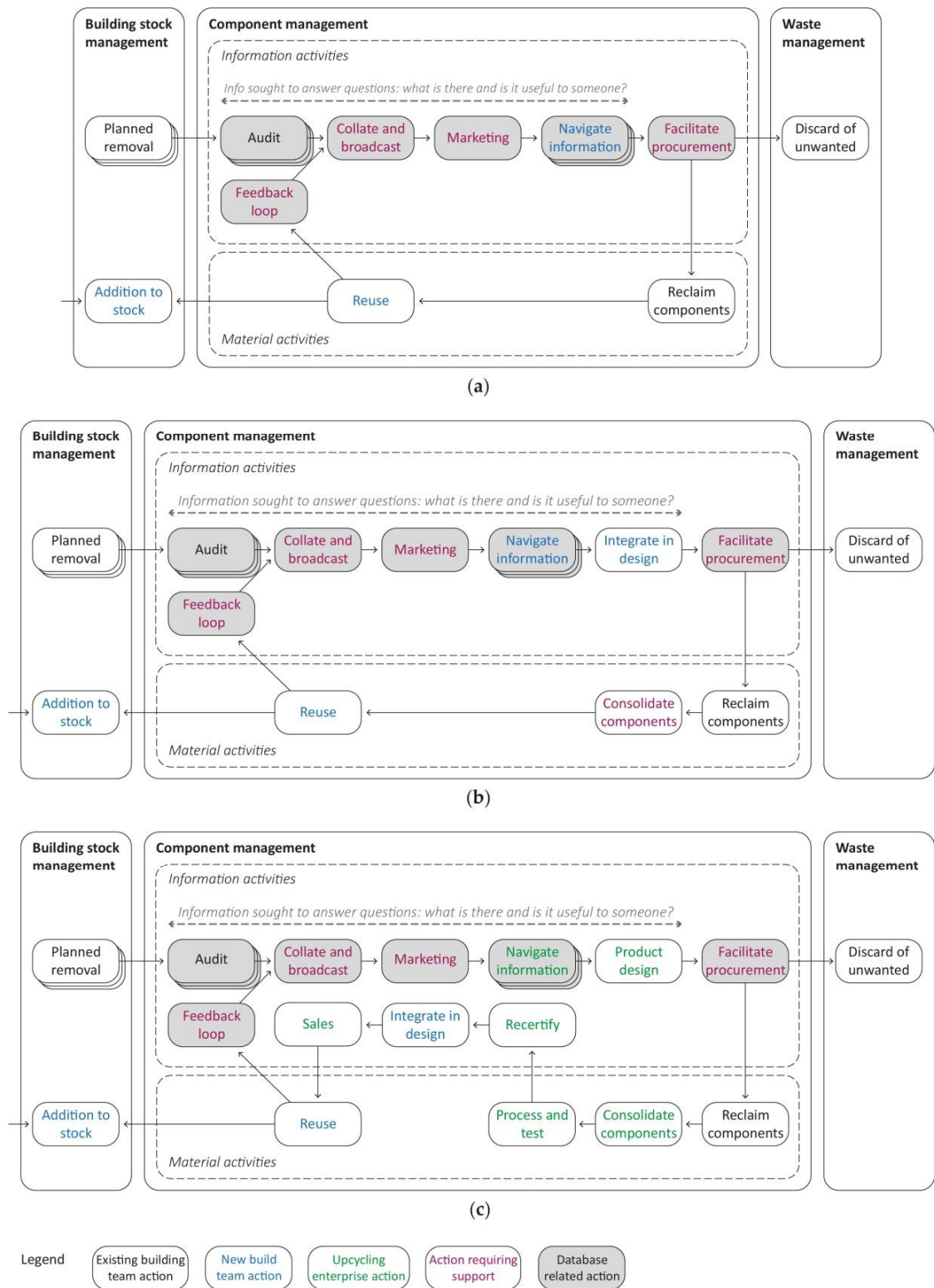


Figure 13: Proposed triage process comprising a series of activities that captures information about existing building components to be removed from stock; makes it visible to a wide community of contractors, designers, and businesses; and determines components' usefulness for: (a) direct reuse – simply substituting specified component for available reclaimed component; (b) direct reuse or repurposing included in design – increasing the scope for using reclaimed; or (c) feedstock for upcycling enterprise – manufacturing certified products that can be used like any other product.

To enable exhaustive exploration of the potential for direct reuse, there is a need for effective information flows through a widely accessible database similar to an RMM. Figure 13a begins to address the identified shortfalls of RMMs by integrating an information gathering regime modelled on pre-redevelopment audits (NFDC/IDE, 2016). At present, the results of audits are used in isolation by the project team and only inform waste management decisions. If, instead, audits from many projects were collated in a database, with components that are to emerge as waste described systematically (and qualitatively as well as quantitatively), it would create a timely array of information. Potential demand actors could navigate the database online and agreements could be reached prior to soft strip, demolition, or deconstruction.

Carrying out a pre-redevelopment audit is incentivised in BREEAM, the environmental accreditation scheme, although as a non-compulsory initiative, auditing is unlikely to become common practice until the benefits are made clear. Legislative change could kick-start this system, for instance, by requiring the submission of an audit for all developments seeking planning consent above a certain size threshold. Intervention at the planning stage ensures that the information is submitted and can be broadcast well in advance of starting on site: in the UK, the period between making a planning application and starting construction is rarely less than six months, and often far longer. Requiring an audit for all projects with significant soft strip or demolition would create a far larger variety and quantity of available components, and a more fertile database from which to meet a new project's needs. The development of standard clauses to enable the specification of items from this source would align reused components with conventional procurement.

The third problem with RMMs as explained – that items may be offered without the warranties required by insurers – causes uncertainty over the quantity and quality of offerings. This is not addressed by the activities illustrated in Figure 13a. In this scenario, components are directly transferred from one site to another without consolidation or warranties, so demand will remain limited to small and informal projects. Introducing a consolidation activity in which components are stockpiled ahead of reuse (Figure 13b) can ensure that adequate quantities are available to meet a larger project's needs, and can help to reconcile project timing and delays (RSA and The Great Recovery, 2015). Evidence from the salvage industry suggests that the consolidation and storage function cannot be performed profitably for the majority of component types in today's context. This would either need to be supported as part of public authorities' goals of improving the environmental impacts of construction, increasing urban management of a city's own waste, and creating additional employment (e.g., by allocating pockets of publicly owned land and resources to manage component storage); or the consolidation function would need to be carried out by private intermediaries that subsidise the cost of consolidation as part of a larger profit-making enterprise that may include upcycling, testing, and recertification (Figure 13c).

Such private intermediaries, operating between supply and demand, may carry out only minor work, or they may undertake new processes not currently recognised as separate waste

management options. Necessarily, they would add significant value to their feedstocks for their business models to be viable. It is the database that focuses the creativity of entrepreneurs, academics, and designers on the invention of new uses for existing building components. The emergence of upcycled and recertified products is the factor that could ultimately expand the remit of reuse beyond niche projects and into mainstream construction, allowing a far greater proportion of components to be retained locally at high value and performance. Costs and lead-in times would become more competitive with primary products as flows increase (Gorgolewski et al., 2006).

This commentary must be seen in the light of the many barriers reported in the literature (e.g., Adams et al., 2017; Chini and Bruening, 2003; Dahlbo et al., 2015; Hradil et al., 2014; Zou et al., 2015) which have at their root the relatively high price of urban land and labour in comparison to those of materials. Increases in primary resource prices and price volatility may be forced upon the industry over time (McKinsey Global Institute, 2011) or early correction of these rises to avoid 'hitting the wall' (Robèrt et al., 2002) may be brought about through tax reform. Many authors have investigated forms of increase in the taxation of non-renewable resources and reduction in the tax burden on employment in order to capture the negative externalities of resource use and encourage the use of the plentiful renewable resource of human labour (Allwood et al., 2010; Antosiewicz et al., 2016; European Commission, 2011; Nakajima, 2000; Stahel, 2013; Wijkman and Skånberg, 2015). The industrial establishment resists such measures, though landfill taxes provide a precedent for top-down government intervention bringing about widespread, positive change (Allwood et al., 2011). Regulatory drivers (such as limits on whole life carbon or measures to incentivise the use of materials with low embodied carbon) may also strengthen the economic case for component management. Until such changes are brought about, either proactively by governments, or passively by a shifting global economic context, stimulating reuse will remain a challenge.

To look at the economic situation another way, if these changes are considered inevitable in the long term, efforts now to evolve C&D waste management towards component management are a bulwark to the resilience of the construction industry, and to our future prosperity.

Limitations and further research

The analysis of case studies attempted to draw conclusions that hold true for C&D waste management in urban environments. However, the critical realist philosophy adopted accepts that the particular phenomena under scrutiny and the conditions under which they arose are dynamic; interpretations are limited to their time and place and cannot necessarily be generalised to a wider context.

The potential of reuse to reduce disposal costs for waste generators and reduce material costs for new construction has not been adequately demonstrated. To increase confidence in the case for changing industry practices, or introducing legislation to stimulate component

management, further research is required. This section suggests that such research could interrogate aspects of an effective system of component management, such as the nature of information required; means of efficiently gathering this data; and opportunities for adding value to specific waste streams through new upcycling business models. These needs spur the research objectives that are addressed in the following chapters.

4.2.4 Conclusions

The construction industry has made considerable progress in its management of waste since the 1990s, when disposal in landfill was common. However, the now-prevalent system of recycling does not capitalise on the value of existing components, and wastes embodied environmental impacts. Reuse, repurposing, and upcycling offer the potential to improve upon waste management, but the decision to discard components frequently goes unchallenged. This is underpinned by:

1. a failure to identify components in advance – current waste reporting is retrospective and classified in coarse material categories, is geared towards waste management, and does not identify specific components' qualities;
2. uncertainty over the usefulness or value of components to others – unlike recycling, reuse suffers from a vantage point problem of knowing what is of use elsewhere; as a means of overcoming this problem, RMMs have drawbacks that impede uptake;
3. a perception of cost and programme risk in undertaking reclamation – in the context of (1) and (2), an inability to assess the merit of reclamation; and
4. acceptance of the preferential order of the waste hierarchy – recycling (in any form) becomes the preferred option where direct reuse appears impractical, such that exploration of the potential for upcycling is not supported.

For contractors to reclaim a greater proportion of building components, demand must be identified from the outset, but contractors are ill-equipped to answer the fundamental question of whether components are of use to others. Rose and Stegemann (2018a) therefore developed a 'triage process' in which the onus for producing this knowledge is shared.

In summary, it is recommended that:

- Policymakers stimulate the generation of relevant information at early stages of projects by requiring the submission of a pre-redevelopment audit for all developments above a certain size threshold seeking planning consent.
- Local authorities or service providers develop and maintain a database in which the audit results are collated and broadcast.

- Clients and their design teams use this database to identify and specify useful components well in advance of demolition.
- Researchers and entrepreneurs use the database to identify underused components, for which environmental and economic improvements upon conventional recycling can be developed, and, in due course, deliver recertified upcycled products.

Many of the risks and constraints associated with reused materials would be overcome by successful upcycling, allowing a wider array of clients, contractors, and designers to adopt their use. The triage thus provides a framework for the robust exploration of direct reuse, and focuses creativity already present in and around the construction industry on the invention of new uses for existing building components. In doing so, it contributes to an emerging system of component management, in which those components that can be retained for reuse are separated out from those for which waste management is the best option.

4.3 Synthesis of the initial investigation with industrial sponsors' perspective

At the outset of the doctoral project, the engagement with the industrial sponsors and their contractors meant there was an implicit ambition to find means of improving practice from within organisations. What can a housing association do differently to bring about a more resourceful use of existing building materials? Senior members of Poplar HARCA and Tower Hamlets Homes were conscious of the waste produced by their processes of refurbishment and regeneration. The notion that some of this could be reused or more locally recycled for use in their own developments is enticing, and does already happen at the level of on-site use of crushed concrete and masonry as piling mats. However, achieving higher value forms of component recirculation remained elusive. Section 4.2 explored the reasons for that, acknowledged the systemic nature of the problem, and began to address its complexity.

The constraints on reclamation, reverse logistics and reuse that this thesis reviewed in the literature (section 2.4.1; Hosseini et al., 2015) correspond closely with the empirically observed barriers identified in the case studies in section 4.2 (Table 30 in Appendix P). Organisations like Poplar HARCA and Tower Hamlets Homes could take action by establishing procurement rules that require contractors to reclaim or reuse components, and helping them to facilitate these practices, but the study suggests that such moves would be stymied by an unfavourable context. In that case, who is to act upon this research? Section 4.2 explains that the transition from waste management to component management must arise from reform on many fronts. It suggests the roles and responsibilities of various parties, and suggests decisive policy intervention is needed to galvanise the generation of information about existing building components.

Section 4.2 addressed the first research objective. It contributed a description of the current system of C&D waste management, and an explanation of the structures and mechanisms that appear to underpin decisions to discard potentially reusable components. In systems engineering terms, it located and described the specific problem to be addressed within the existing context system. In a city like London, the urban metabolism of refurbishment, demolition and regeneration has the potential to create a supply of, and demand for, secondary building components. This chapter indicated how further investigation might better connect supply and demand in component management. It is not within the scope of the doctoral project to address all of these areas of further research; but Chapters 5 and 6 explore knowledge gaps in the information system and the role of intermediaries respectively.

5 URBAN-LEVEL INTERVENTION AND REALISATION SYSTEMS

5.1 Introduction to information system investigation

The work undertaken in pursuit of the first research objective determined that the critical lack of information about components that make up existing buildings needs to be overcome. This prompts the second research objective: investigating how information about 'existing buildings as material banks' is currently obtained; proposing means of improving information flows to support component management; and testing how this could facilitate the emergence of reuse, repurposing and upcycling ideas.

This thesis includes as Section 5.2, Rose and Stegemann (2018b). Present means of gathering E-BAMB information are reviewed and a detailed picture of industry information needs is created. Potential means of addressing needs through a development of the information-related aspects of the triage intervention system introduced in Chapter 4 are proposed. There are many examples in the literature of proposed databases to facilitate the exchange of information and support a market for reused components (as reviewed in section 2.4.4 of this thesis). Going beyond simply proposing a database, section 5.2 considers the integration of a database into C&D procurement processes, and connections to other areas of evolving research.

In section 5.3, the investigation of E-BAMB is synthesised with the triage intervention system. The theory developed in Rose and Stegemann (2018b) – stages of 'reflection' and 'planning' in the research cycle – leads into action as aspects of the triage are tested through a series of live case studies, reported in section 5.4.

5.2 Characterising existing buildings as material banks (E-BAMB)

5.2.1 Introduction to the potential use of E-BAMB information

To meet ambitious global greenhouse gas emissions targets, the UK and many other countries must improve emissions associated with buildings (Giesekam et al., 2015). In the most extreme scenario modelled by Giesekam et al. (2016), designers must find ways to reduce embodied emissions across all new buildings by 67% by 2027 to achieve interim targets. Recent work framing a view of 'buildings as material banks' (BAMB; Debacker and Manshoven, 2016), within which components are retained at high value for future reuse, tends to focus on new buildings (Durmišević, 2015). The intention is to create a future end-of-life building stock composed of recoverable components that will remain useful in the face of unpredictable changes in standards, technology, economics and societal needs. This will not secure reductions in embodied emissions in the timeframe set out by Giesekam et al. (2016). However, reuse of *existing* building components could make a contribution. Reuse, the 'inner circle' of the circular economy, is gaining increasing attention, not only as a means of reducing embodied emissions (e.g., Dunant et al., 2017; Gorgolewski, 2008; Ness et al., 2015); but also in helping to address other environmental impacts of the construction industry.

At present, a limited selection of high value components are reclaimed from existing buildings and traded by the salvage industry (CRWP and Salvo, 2007). Environmentally beneficial improvements upon dominant recycling processes are not necessarily limited to direct reuse; they may also include repurposing and upcycling. Some may argue that little improvement upon recycling is (currently) feasible for the majority of materials; but this is an assumption. It cannot be tested because information about components, and the components themselves, are not available to the potential demand side of the market. To be able to test this assumption, and keep testing it as the economic context evolves, there is a need to re-frame existing buildings as material banks, rather than seeing them as 'waste in waiting' (Giesekam et al., 2015). To support this change, this section develops a framework for the collection and application of E-BAMB information. The needs of the demand side of the market are taken into account so that the potential to reuse, repurpose and upcycle components can be exhaustively checked before they are consigned as waste.

5.2.2 Policy context and research objectives

Reuse is supported by policy at many levels. The EU Waste Framework Directive (European Commission, 2008) requires member states to embed into law the principle of the waste hierarchy. The Clean Growth Strategy (HM Government, 2017), The Waste Management Plan for England (Defra, 2013), the London Environment Strategy (GLA, 2018a) and planning policy documents including the London Plan (GLA, 2016) and local plans, all stress the importance of reuse as a means of waste prevention. Planning guidance in London recommends the application of the waste hierarchy, use of reclaimed components in preference to materials with

recycled content or new products, making existing components that cannot be reused on-site available for reuse elsewhere, and sourcing materials locally (GLA, 2014). London's circular economy route map advocates the introduction of targets for reuse in construction, and development of markets for reused products (LWARB, 2017). The sustainability checkpoint in Stage 0 of the RIBA Plan of Work calls for a strategic review 'including reuse of existing facilities, building components or materials' (RIBA, 2013).

However, the waste hierarchy's preferential order can be circumvented (Van Ewijk and Stegemann, 2016) and counter-arguments are allowed to justify ignoring planning guidance. If the benefits of reuse, repurposing and upcycling are to be achieved, the policy framework must move from recommendations that favour reuse into enforceable requirements and supporting measures that help to bring it about in the mainstream. Markets for secondary materials are identified by the EU Circular Economy Package (European Commission, 2015) as an area for development. Specific levers need to be identified and used to create a functioning market in reused building components.

There is consensus in the academic literature that a scarcity of information about the existing building stock acts as a barrier to effective management of end-of-life components (Ali, 2016, 2012; Debacker and Manshoven, 2016; Densley Tingley et al., 2017; Horvath, 2004; Hurley, 2003; Poelman, 2009). Iacovidou and Purnell (2016) explain the need for component quantity, availability, size and properties to be audited and communicated to create liquidity in the market. However, the changes needed to achieve a wholesale shift towards a characterisation of E-BAMB are poorly understood. This section critically analyses current means of generating E-BAMB knowledge, and frames a direction for further work, as a precursor to overcoming other constraints to reclamation and reuse. Its goals are to:

1. Critically review existing practices and research that can contribute to an understanding of E-BAMB;
2. Examine the limitations of these practices for supporting reuse, repurposing and upcycling;
3. Show how new approaches to generating E-BAMB knowledge can address present shortfalls;
4. Discuss these proposals in the light of other relevant advances to illustrate a scenario for future knowledge of E-BAMB.

5.2.3 Review of existing buildings as material banks research and practice

Categorisation of approaches

Table 14 identifies existing and emerging practical and research approaches to gathering E-BAMB information, for discussion below.

Table 14: Approaches towards gathering E-BAMB information

	<i>Demand side can seek information about existing building components by...</i>				
	...leading search themselves	...leveraging practice-based knowledge and networks: with waste producer	with 3 rd party material handler	with 3 rd party information handler	...drawing on evidence-based knowledge
<i>Information about supply can be generated by...</i>	...analysing original design	As-built information	As-built information	-	Future: BIM for new buildings
	... keeping records of built assets	-	-	-	Public records; owners' stock condition surveys
	...estimating components while in use in buildings	Demand-led 'harvest mapping'	Supply-led demolition planning, pre-redevelopment audits	Salvage industry expertise	Reused material marketplaces
	...applying novel techniques to measure components while in use	-	-	-	In-use stocks research; waste prediction research
	...identifying once removed from building	Scavenging	-	Salvage yards; waste flow monitoring	BIM for existing buildings: automated scan-to-BIM research
				Collated waste transfer statistics	Waste quantification research

'As-built' information about existing buildings

When available, drawings and specifications documenting construction and maintenance of buildings provide a useful reference for further adaptation of buildings or for assessing potential use of components to be removed from a building. An example is the archive maintained by the UK government of its own estate (The National Archives, 2012). However, where records have been retained through a building's lifespan, they are typically used internally within the project team to aid design, rather than in an aggregated way that could be drawn upon by demand from outside the project team. More often, documents from the time of construction are unavailable, incomplete or unreliable (Brewer and Mooney, 2008; Gorgolewski and Ergun, 2013; Guggemos and Horvath, 2003; Macozoma, 2001; Volk et al., 2014). In the UK, pre-construction drawings submitted for Building Control approval are deposited with local authorities. Anecdotally, attempts to access and use such records are rarely successful: pre-digital records may not be available; physical drawings may have deteriorated; they may not provide a full, detailed

description of components; construction details may have changed post-submission without updating local authority records. The general scarcity of as-built information means that systems for its use are not in place.

Building information modelling (BIM) for existing buildings: automated scan-to-BIM research

New buildings will increasingly be accompanied by digital records produced through BIM. Coupled with material passports (Luscuere, 2017; Ness et al., 2015), and the miniaturisation of Internet of Things devices (Heiskanen, 2017) this offers the prospect of a future end-of-life building stock for which comprehensive E-BAMB information will, in some cases, be readily available. It is becoming increasingly efficient to generate BIM for the existing building stock, based on laser scanning and (semi-)automated object recognition processes (Arayici, 2008). This can be used as an alternative to manual survey work, to produce as-built drawings of historic structures (Barazzetti et al., 2015; Murphy et al., 2009), and potentially to improve demolition/deconstruction planning (Volk et al., 2014). The process of turning a geometric scan into a 'semantically rich' BIM model with component attributes is still in its infancy in 2018. However, in due course, texture-based recognition and surface penetrating scanning techniques may make it possible to identify materials both on and below the surface (Volk et al., 2014), to produce an inventory of existing components (Volk et al., 2015) that could be embedded within an E-BAMB information system. By sharing inventory information when buildings reach end-of-life, designers elsewhere would be able to check forthcoming availability of components and assess their suitability for use in new projects (Swift et al., 2015).

'In-use stocks' research

'In-use stocks' research (Kohler and Hassler, 2002) attempts to describe stocks and flows of materials at city, region, or country-wide scale (e.g., through material flow analysis; Tanikawa et al., 2002) (see section 2.2.3 of this thesis). These studies rely on various assumptions, such as homogeneity of material composition across categories of building types and age classes (Augiseau and Barles, 2017) to arrive at overall tonnages of material per capita (e.g., Kral et al., 2014; Tanikawa and Hashimoto, 2009; Wiedenhofer et al., 2015) or material intensity per building area or volume (e.g., Bergsdal et al., 2007; Kleemann et al., 2016). Data at this level allow, for example, projections of future material demand, but are not suited to practical application at project level. In economy-wide studies, most of the materials assessed will remain in use for decades.

Quantification of materials in use (as well as quantification and prediction of waste flows) tends to categorise into material groups for recycling, rather than into component groups for reuse. These studies generally do not grapple with the development of the demand side of a reused component marketplace. However, there are examples of in-use stocks research that have reuse as the specific goal, and which narrow the focus to a single component type. Ergun & Gorgolewski (2015) investigate Toronto's detached housing stocks with a particular focus on

brick. Huuhka et al. (2015) develop a detailed inventory of prefabricated concrete panels in Finnish 1970s mass housing. They include qualitative data such as the form and condition of panels: information that is essential to a designer wishing to reuse or an enterprise wishing to assess the feasibility of upcycling such a waste stream. It would be valuable to develop this field further to reach the granularity needed to inform industry at project level.

Supply-led demolition/deconstruction planning and pre-redevelopment audits

The UK Site Waste Management Plan Regulations (HM Government, 2008; repealed 2013) were intended to encourage contractors to predict forthcoming waste streams, partly to allow a proactive approach to reusable components (Resource Efficient Scotland, 2017). As stated in section 4.2, it is common for data to be collected retrospectively by waste management companies, when skips reach WTSS, by which stage, both the materials and the information about them are aggregated in a way that reduces their usefulness (Rose and Stegemann, 2018a).

Research has emphasised the importance of pre-planning of demolition (Pun et al., 2003; Pun and Liu, 2006). The Demolition Protocol (ICE, 2008) and Resource Protocol (NFDC/IDE, 2016) seek to bring this about through pre-redevelopment audits (or pre-demolition audits in the former document). They combine a desk-based survey of existing information with a site survey to produce an inventory. In the development of the London 2012 Olympic Park, application of the Demolition Protocol helped to drive the reclamation of nine steel-framed buildings for reuse off-site, and on-site recycling of 400,000 tonnes of crushed concrete and masonry (Carris, 2011). A reclamation audit was undertaken and the findings shared with designers of new parts of the Olympic Park through a database, site visits and workshops (BioRegional, 2011). Although reuse did not play a significant role in meeting the overall target of at least 90% reuse and recycling for the Olympic Park as a whole, various items were reclaimed and reused (Carris, 2011).

Whereas the Olympic Park development's own needs provided a moderate level of demand, a smaller project may present limited opportunities for on-site reuse; however, making information from audits available to industry at large – a city-wide community of designers and contractors – would expand reuse opportunities. The value of pre-redevelopment audits is, however, presently limited by the lack of a mechanism for their exposure beyond the project team. Furthermore, as pre-redevelopment audits are a voluntary tool, and attempts like those made in the Olympic Park development are rare, they are not familiar to specifiers and purchasers as a potential form of supply. Such project-based information gathering needs to be part of a wider framework; a form of supply. If achieved, this would motivate clients and contractors to produce thorough audits.

Demand-led harvest mapping and the 'superuse scout'

The Dutch architecture practice, Superuse Studios, have developed an innovative approach to procurement of materials for their projects. In their means-oriented approach to design, the available materials provide the starting point and impetus for meeting the project brief (Pereira et al., 2016). A process known as harvest mapping is used to discover what is available (Jongert et al., 2011; van Hinte et al., 2007). In the early stages of a project, the area around the site is scouted for available waste streams, initially considering a 25 km radius. Potential sources are visually represented on a map, providing a material catalogue to assist the design team and a means of communicating material choices to the client (Jongert et al., 2011).

The lack of established systems of E-BAMB information means that harvest mapping is a time-consuming process. Superuse Studios extend their remit beyond normal architectural design; they employ staff and consultants to search for and document available materials, and host a website with information about one-off and continuous waste streams that could be used by other architects (Superuse Studios, 2017a). They anticipate future codification of this knowledge in a new profession, the 'superuse scout' (van Hinte et al., 2007: 14). Superuse Studios' approach offers a compelling alternative vision of practice. Their portfolio (Superuse Studios, 2017b) shows how the application of creativity to information about unwanted materials can lead to new repurposing ideas. However, the change of process involved in means-oriented design (Gorgolewski, 2008), and the additional burdens that the architect would currently take on to implement it, constrain uptake in mainstream construction.

Reused material marketplaces (RMMs): supply-demand interface

Without ready supply information to draw upon, *demand-led* harvest mapping is time-consuming and requires a radical change in approach to design. Without a mechanism for reaching demand beyond isolated project teams, *supply-led* pre-redevelopment audits are likely to produce little opportunity for reuse. RMMs appear to offer a plausible interface between 'supply projects' and 'demand projects': a digital forum for exchanging unwanted items.

Since the 1970s there have been concerted efforts to form networks comprising generators and users of waste (Chen et al., 2006; Gorgolewski et al., 2006). As information platforms, those focusing on the construction industry function like eBay: sellers post information about available items, and buyers can browse, typically by categories ('plastics', 'bathroom' etc.) and location. Most have exhibited little success (Chen et al., 2006; Rose and Stegemann, 2018a; Table 15). To fulfil their potential, RMMs need to serve both the supply and demand side of the market.

Table 15: A selection of reused material marketplaces (all websites accessed 03 April 2014 and 25 October 2017)

Reused material marketplace	Location	Methodology	No. of items April 2014	No. of items October 2017
Construction Material Exchange (cme.resourceefficientscotland.com)	Scotland	Web-based; offers and requests	1 item posted	2 items posted
Enviromate (enviromate.co.uk/marketplace)	UK	Web-based; offers and requests	n/a	637 items posted
Globechain (globechain.co.uk/construction)	UK	Web-based; offers and requests; membership	n/a	172 items posted
Harvestmap (oogstkaart.nl/oogstkaart)	Europe	Web-based map of resources	198 items posted	102 items posted
Loop (loop-hub.co.uk)	UK	Web-based; map and offers and requests	n/a	15 items posted
Rebuild North East (rebne.co.uk/building-materials)	Tees Valley	Warehouse- and web-based	43 items posted	Discontinued
Recipro (recipro-uk.com)	UK	Warehouse- and web-based; pick up from sites, sell at warehouse	Hundreds of items available	209 items posted
Salvo Materials Information Exchange (salvomie.co.uk/index.html)	UK	Web-based; offers and requests	Unknown	9 items posted
Trade Swap (trade-swap.co.uk)	UK	Web-based; offers and requests	31 items posted	Discontinued
Trade Leftovers (tradeleftovers.com)	UK	Web-based; offers and requests	6 items posted	0 items posted

From the supply perspective, posting unwanted items on RMMs is not an established practice for contractors (Rose and Stegemann, 2018a). There is little incentive to adopt it as a new practice unless there are good prospects of making sales. From the demand perspective, designers require information well in advance of the potential purchase, certainty about the quantity and the quality of the items offered, and a wide choice. At present, items are usually offered at the time that they arise as waste rather than in advance. This precludes the opportunity for them to be incorporated into design development. As indicated in section 4.2, contractors lack trust in RMMs (Rose and Stegemann, 2018a). In terms of choice, the active RMMs identified in Table 15 have an average of 143 items currently available, while the products table of Uniclass 2015 (NBS, 2015) lists more than 6,700 construction product types. The market segment of demand projects that can take advantage of components made available on RMMs is therefore severely limited by the need to be less selective and to make immediate use of materials.

Attempts to improve the efficacy of RMMs by using GIS (Ali, 2012; Susanty et al., 2016), and big data (Bin et al., 2015) and BIM (Ali, 2012), focus on optimising matches between supply and demand. However, they do little to address the fundamental barriers to use of RMMs on the demand side, or the consequent lack of motivation to offer materials on the supply side. To be more effective, the RMM platform needs to fit into a strategy for gathering structured and timely information from a wide range of supply projects, demand projects, or both. Partnering

approaches, such as Royal BAM Group working with IBM on a new 'Circular Building Platform', may garner significant volumes of supply and demand data through the direct involvement of a major construction company, and thus increase the likelihood of creating effective exchanges. New RMMs would also benefit from making a thorough diagnosis of the reasons for previous failures.

Waste flow monitoring

When none of the above approaches are taken, the first picture of a building's material content comes as a set of waste streams, as described in section 4.2. Materials are described as waste under European Waste Catalogue codes (European Commission, 2000). Industry monitoring of waste flows at WTSs is too late, and too undifferentiated, to aid in reclaiming components for reuse (Rose and Stegemann, 2018a). The lack of granularity means it fails to provide even a retrospective understanding of E-BAMB.

5.2.4 A coordinated approach to E-BAMB knowledge generation

Overview

This section proposes that to address the weaknesses identified above, there should be a coordinated information system that draws upon and develops out of existing practices. At the centre is an E-BAMB database, or virtual warehouse, like an RMM, but embellished with information from refocused pre-redevelopment audits, in-use stocks research and scan-to-BIM research (Figure 14). The following subsections discuss the information flows and activities labelled (A)-(F) in the diagram.

Audit: focus of data collection and nature of data

For the reuse opportunities identified in pre-redevelopment audits to be more clearly apparent, the description of components should be based on an established classification system (e.g., the elements or products table of Uniclass 2015, or the Common Arrangement of Work Sections; CPIC, 1998), rather than on waste categories. The audit should capture qualitative information, in the form of a photograph in the first instance, alongside location, expected timing, approximate quantities and potential embodied carbon savings (BioRegional, 2011; Iacovidou and Purnell, 2016). If as-built records exist, this will provide the starting point for the audit, though changes to the building over its lifetime may require this information to be updated. In future, there may be more efficient ways to create inventories of existing building components, such as through the use of detailed models developed by in-use stocks researchers, or automated scan-to-BIM technology.

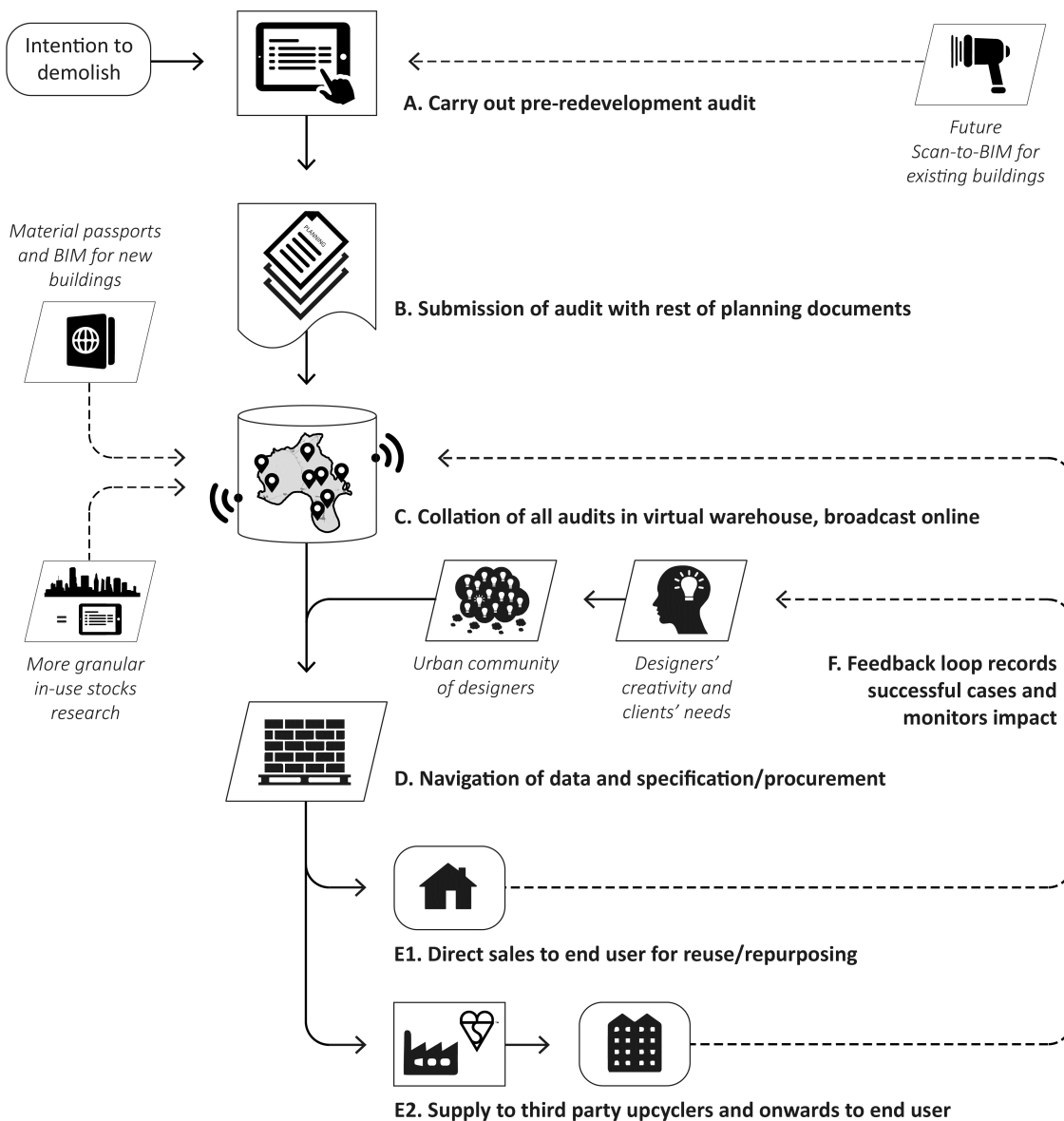


Figure 14: E-BAMB information system flow diagram. Collectively these steps form part of a 'triage process' that separates out components for reuse, repurposing and upcycling from those for which downcycling or energy recovery are the best option (Rose and Stegemann, 2018a).

Submission: responsibility and timing

Once there is a track record of successful examples of pre-redevelopment audits and E-BAMB information being shared, materials being identified, reclaimed, profitably sold and reused, the motivation to carry out audits can confidently be expected to increase. However, a legislative nudge appears necessary to create the conditions for such examples to emerge, and to build the evidence and confidence to support widespread adoption. For example, the production of E-BAMB information could be achieved by making a pre-redevelopment audit mandatory for planning consent for projects (above a certain size threshold) that involve demolition or soft strip. If initially the threshold is set high, this would focus attention on developments with the largest potential for waste prevention gains. The threshold could be lowered incrementally, in

tandem with a growing capacity in industry for carrying out audits and reclamation, increasing availability of storage and growing demand for secondary components. As norms shift and these processes become common practice, transaction costs would drop.

Materials advertised on RMMs are often about to be discarded, which limits their availability to projects that can make immediate use of materials (Figure 15). Projects that cannot make immediate use of materials would rely on a 'supply and demand storage buffer' (RSA and The Great Recovery, 2015) until they have reached construction stage (Figure 16). Introducing the requirement for a pre-redevelopment audit at planning stage allows a period of time for incorporation of components into design, specification and procurement (Figure 17).

When estimated and actual construction project timeframes differ, hampering smooth supply to demand, city-scale material availability inventories would reduce the problem. Rarely will the need for intermediate storage be eliminated altogether, but it may be reduced to an extent that makes warehouse costs or site storage viable.

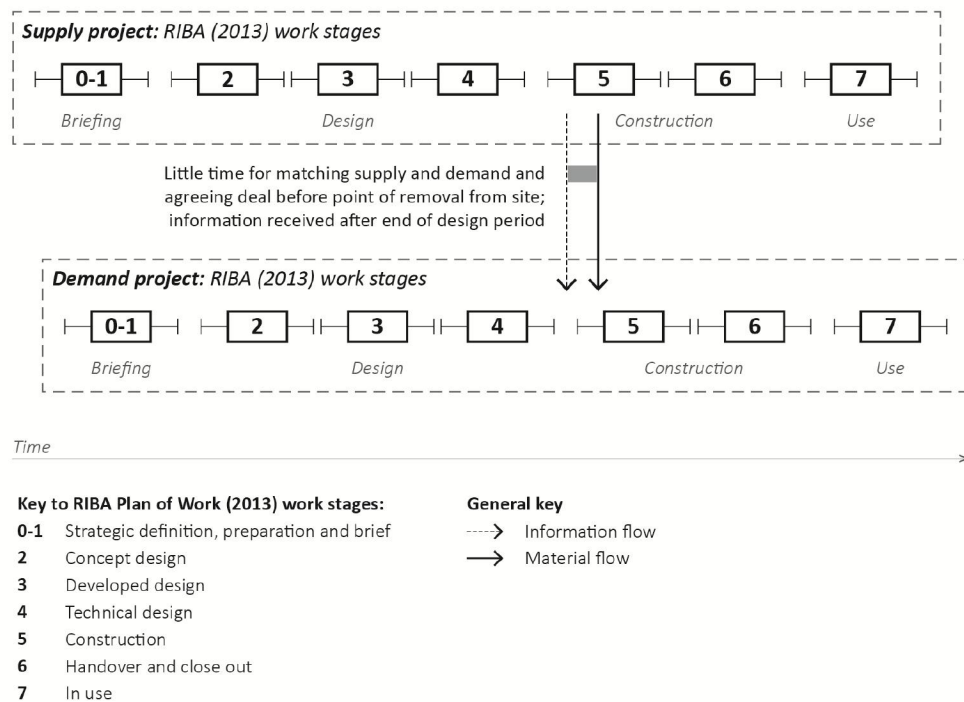


Figure 15: Typical use of RMM to facilitate direct exchange between supply and demand projects. Components not identified in advance, so demand project receives components and immediately uses them in construction. Some potential for direct substitution of specified products, but generally reused components will need to be designed in to the scheme during Stages 2-4. Thus types of demand projects that can reuse or repurpose components at late stage are severely limited.

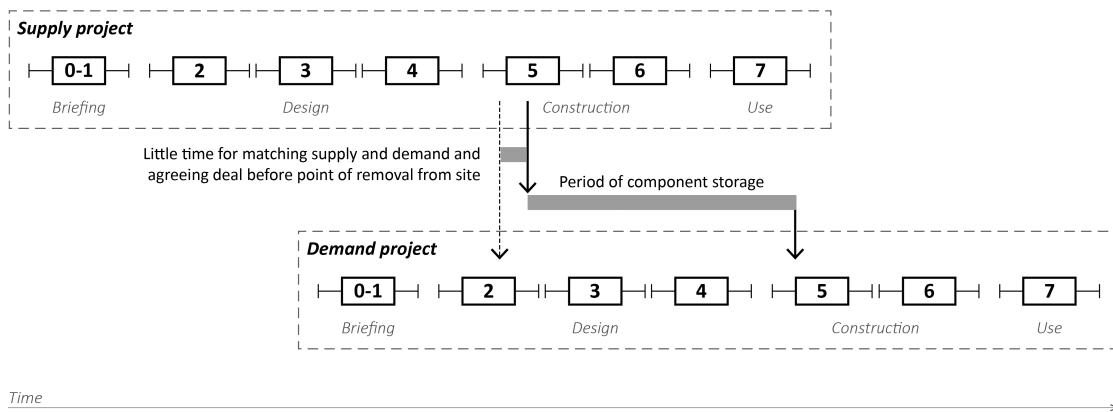


Figure 16: Use of RMM with storage available on one or other site or in separate storage facility. Reuse or repurposing designed in to demand project during Stages 2-4 and components used later when it reaches Stage 5. Risk of components being put into storage but ultimately not used. Storage may be prohibitively expensive. (For legend refer to Figure 15.)

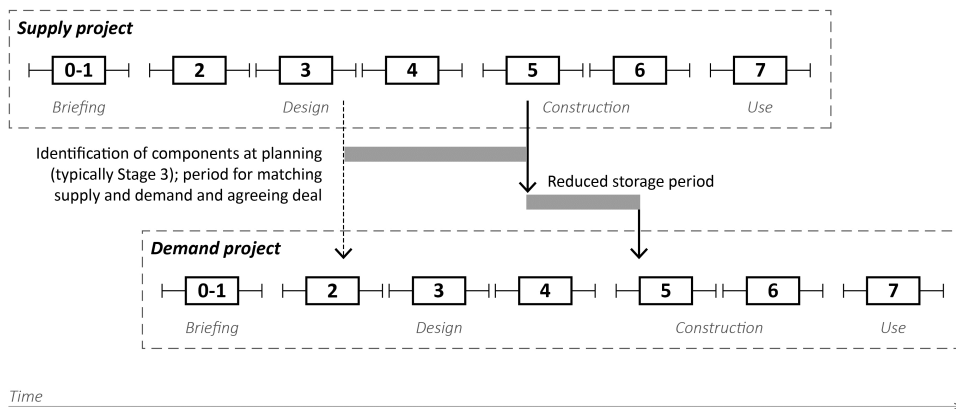


Figure 17: Early production of E-BAMB information. Supply project chosen on the basis of similar expected start on site, to avoid or minimise period of storage. Reuse or repurposing designed in to demand project during Stages 2-4; further component information gathered as necessary; condition of components post-reclamation agreed and price negotiated. Storage period reduced but may still be prohibitively expensive. Risk of project delays leading to a failure to supply at agreed time; demand project would then have to switch to another supply project or conventional suppliers. (For legend refer to Figure 15.)

Broadcast: collation and sharing of information

E-BAMB information submitted to the local authority at planning stage in a standardised format can be collated in a virtual warehouse, broadcast online and promoted to the demand side of the market. Many potential new uses could be expected to emerge from the collective creativity of designers, contractors, manufacturers, entrepreneurs and academics. For example, a study of components from decommissioned oil and gas rigs exposed the results of a 'pre-landing audit' to various industry participants in an ideas workshop. In two hours, thirteen participants had come up with 186 unique ideas for 24 identified components (RSA and The Great Recovery, 2015). An ideas workshop is not bound by the need to implement proposals, but if E-BAMB information were to reach a large urban community, reuse ideas would be driven by real

needs as well as collective creativity. For instance, pre-fabricated concrete building components that appear to have no use in their original form may be repurposed as a hard landscaping surface instead of new paving; as thermal mass inside a glazed foyer; or after being cut and polished, as a backdrop to café seating. Many ideas may prove unfeasible, but casting the net widely increases the chances of the emergence of successful reuse, repurposing and upcycling opportunities.

Navigation: accessing and using information

Ongoing developments in electronic search capability will enable efficient scouring of a large E-BAMB database. As well as the capability to search by location and material type, the use of an established classification system in the audit would allow categories of product to be matched automatically against demand requirements. Less conventional search capability will be required to identify value-adding repurposing of a component from one product category to serve a function in another. Repurposing is a creative act, but this creativity could be codified within the database by linking instances of components' transfer from original uses to new uses. Revisiting the prefabricated concrete example, if one exchange saw panels successfully repurposed as hard landscaping, the database could flag up forthcoming sources of prefabricated concrete panels for the next demand project seeking hard landscaping. Thus, a niche repurposing project has a trajectory to repeated application, and potentially to high volume upcycling, facilitated at scale by a third party.

Having identified possible materials for reuse, demand projects' designers would need to find out further information, in the same way that they would for a new component. Whereas the investment of time in researching a conventional product may pay back through use in multiple projects, reclaimed components are likely to need new investigations each time. Detailed qualitative and quantitative audit information in the first instance will minimise the need for site visits to gather more information. This will increase confidence on all sides that the transaction will be successful. Standard clauses would need to be developed for specifying components from the virtual warehouse, to align reuse with conventional procurement. The price and condition of recovered components would need to be agreed; supply side developers would need to specify, in demolition contracts, any recovery operations that differ from typical demolition.

Component flows: reuse, repurposing and third party upcycling

Direct reuse or repurposing of components turns developers and demolition contractors into suppliers, for which capacity would need to be built. It also makes the sourcing of materials a key driver in the early design stages, potentially influencing layout, structure and other parts of the design, and requiring a change to the design process (Gorgolewski, 2008). It will take time for capacity to build in the construction industry for these changes. Drivers include increasing recognition in industry of circular economy principles and their application in construction

(Adams et al., 2017), and external factors such as potential increases in resource prices, carbon taxation and regulation of whole life carbon (Rose and Stegemann, 2018a). However, without relying on these pressures to change design practices, this section envisages a process even more in line with current developments in procurement of both demolition and new construction: private third parties as intermediaries between the supply and the demand projects (Figure 18).

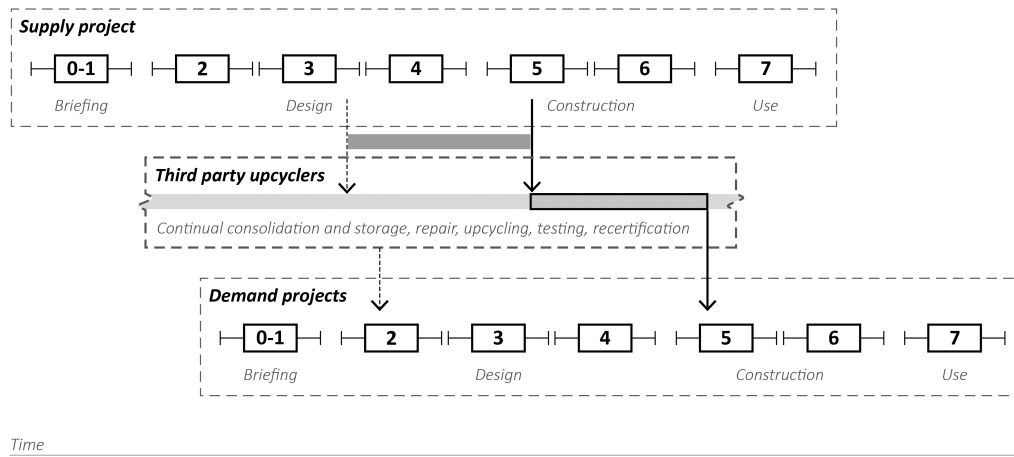


Figure 18: One or more third party intermediaries between supply and demand projects. Enterprises exploit new business opportunities based on E-BAMB information. Consolidation, upcycling, testing and recertification add value, and allow products to reach larger market segments. Products meet same standards as primary equivalents, or create new standards. Product information available to demand projects at any time, more akin to a conventional supply chain. Intermediaries resolve supply project delay issues. (For legend refer to Figure 15.)

As stated in section 4.2, intermediaries will have to add significant value to their feedstocks to cover costs. Efficiency gains through the E-BAMB information system may somewhat reduce salvage yards' supply costs, but increasing the scope for third party reuse beyond high-end architectural salvage is likely to remain a challenge. Therefore, there is a need for new value-adding processes that maximise the difference between cost of feedstock (or incoming waste disposal fees), and the market price for resulting products. Development of upcycling business opportunities is most likely in a situation where potential feedstocks are made visible and available. In a mature state, intermediaries would consolidate and process feedstocks continuously, absorbing or mitigating the effect of project delays, and creating a viable alternative supply chain. The demand side need for certainty over quality and quantity would be met by recertifying products and making them available within reasonable lead-in times. Local processing of discarded building components would create various new employment opportunities, and a means for more local private and public spending.

Feedback loop: codifying knowledge and assessing impact

Recording reclamation and reuse facilitated through the virtual warehouse would codify repurposing ideas (as discussed above in regard to navigation). It would also allow measurement of prevented waste, avoided primary material purchasing, and avoided embodied carbon emissions. This data could be used to establish realistic project benchmarks for

reclamation and reuse, informing new incentives e.g., within BREEAM. Life cycle assessments could verify the reductions in environmental impacts. Public procurement could require a quota of materials to be reclaimed from existing building stock, reused in new construction, or both. Embodied carbon savings realised through reuse could contribute to reaching zero carbon targets (e.g., GLA, 2014).

5.2.5 Conclusions

This section has presented a pragmatic assessment of the ways that components in existing buildings can be understood through research and practice. Currently the main methods available for understanding E-BAMB are not effective for enabling component reuse. No single existing approach addresses the full interface of supply and demand, nor are they organised together to form an effective information system. From the weaknesses and strengths of existing methods, the section deduced an improved system for gathering structured and timely information and using it to effect change within industry. In the proposed system, RMMs are embellished with information from refocused pre-redevelopment audits, in-use stocks research and developments in scan-to-BIM technology. The process steps have been integrated into normal procurement procedures. With further development, this would represent an early step in making reuse, repurposing and upcycling possible at scale. Further research into the information system design will be needed to develop its operability, such as the ownership and maintenance of the E-BAMB database, its interface with BIM-enabled specification, and means of navigating components' *qualities* within a large dataset that can facilitate the identification of unexpected solutions to needs.

Existing policy endorses reuse, but mechanisms for implementing it are presently weak. The policy framework must move from recommendations that favour reuse into firm requirements and supporting measures that help to bring it about in the mainstream. To contribute to this shift, the section described how E-BAMB knowledge could be generated and used, as a precursor to overcoming other constraints to reclamation and reuse. Given the uncertain extent of benefits that would accrue, it is ambitious to design a new information system and develop it as a feasible procurement route, and optimistic to call for legislative change. However, without innovations along these lines, the prospects of achieving greater reuse are extremely slim. Advances are hampered by the difficulty of predicting levels of practical adoption of reuse in conditions that remain largely theoretical. Until the information and infrastructure to support reuse exists, it is hard to establish the extent to which it would benefit industry; and until real benefits are proven, it is hard to justify investment in the types of innovation described in this section. Further research could therefore investigate criteria for adoption of reuse and emergence of repurposing and upcycling ideas if the demand side of the market were exposed to more comprehensive E-BAMB information.

5.3 Synthesis of urban-level systems engineering framework

Section 5.2 (Rose and Stegemann, 2018b) explored the generation and use of knowledge about E-BAMB. The idea of an information system with a database at its centre was developed, but the part this plays within the triage intervention system was not explained. This section therefore synthesises the systems engineering aspects of the proposals put forward in sections 4.2 and 5.2.

The systems engineering base model introduced in section 3.3.2 (Martin, 2004) is used to represent the systems under consideration in this research, with their goal of bringing about a system of component management (Figure 19). A brief commentary follows.

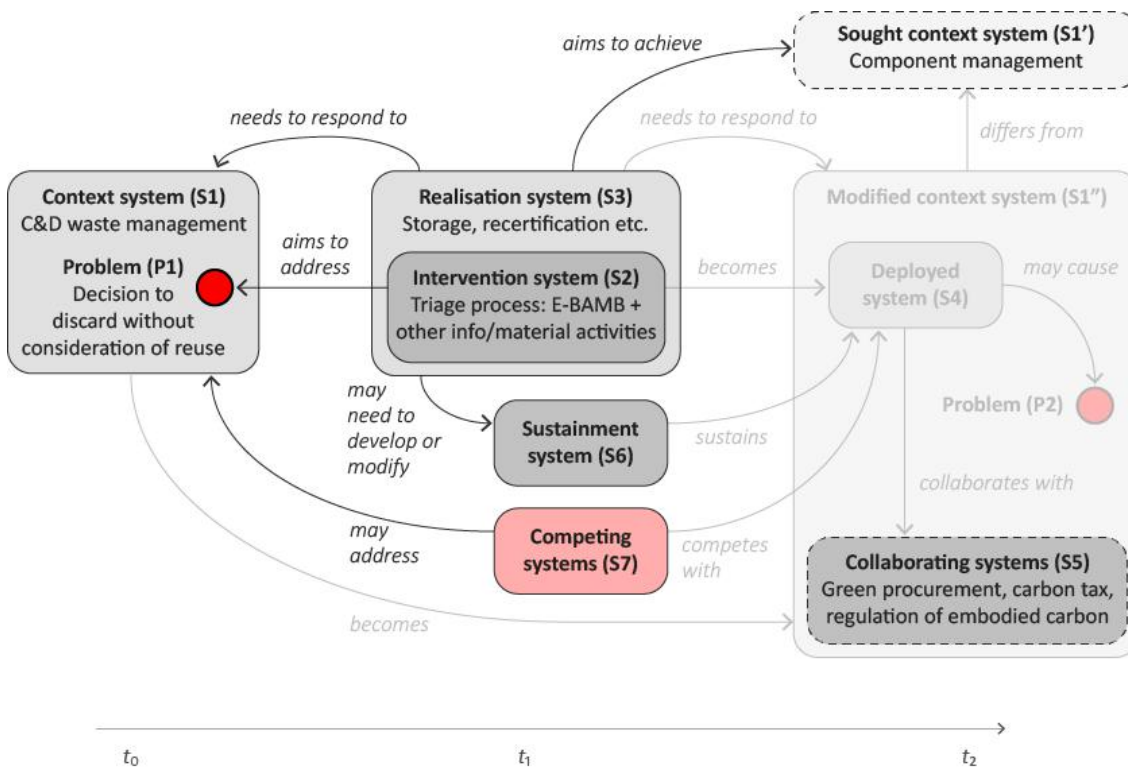
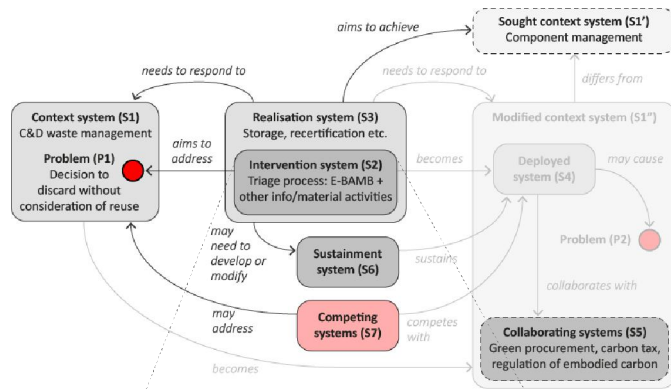


Figure 19: Systems engineering diagram for urban-level component management (base model adapted from Martin, 2004). Subsystems that cannot be described at time t_1 are greyed out.

- Context system (S1): construction industry management of end-of-use materials characterised by a reliance on waste management, as discussed in section 4.2.
- Problem (P1): strong tendency to discard end-of-use components to waste management without considering their potential to be reused, repurposed or upcycled.
- Sought context system (S1'): transition to a scenario in which all reusable components are retained for reuse, repurposing and upcycling in a system of component management, in preference to discarding to waste management.

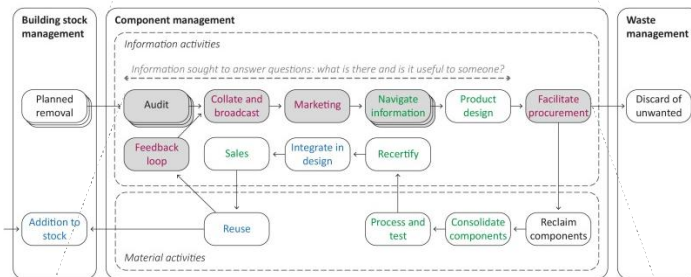
- Modified context system (S1'') is greyed out because only the sought context system (S1') can be described at time t_1 .
- Intervention system (S2): triage for separating out those components that can be reused, repurposed and upcycled from those for which waste management is the best option, comprising both information activities and material activities (Figure 13). Information activities centre on E-BAMB database (Figure 14).
- Realisation system (S3): resources and capacities needed to carry out the triage activities, including E-BAMB auditors, the requirement to submit audit at planning stage, deconstruction and reclamation specialists, stockists with storage spaces, testing and recertification regimes and upcycling enterprises.
- Deployed system (S4) is greyed out because only the intervention system (S2) can be described at time t_1 .
- Collaborating systems (S5): potential developments in the context that would support future deployment of the triage, including green public procurement, greater taxation of non-renewable resource use or carbon, and regulation of buildings' whole life carbon.
- Sustainment system (S6): keeping the deployed system operational is likely to require resources to maintain and promote the E-BAMB database, to manage storage spaces, and potentially to facilitate exchanges.
- Competing systems (S7): the same or a somewhat different problem may be diagnosed and addressed by other initiatives, which compete for resources and attention. For instance, circular economy strategies that aim to improve future reuse may draw policymakers' attention away from the current reuse of existing building components.

Figure 20 provides an overview of the connections between the three levels of systems diagrams used in Chapters 4 and 5, to clarify their nested arrangement.



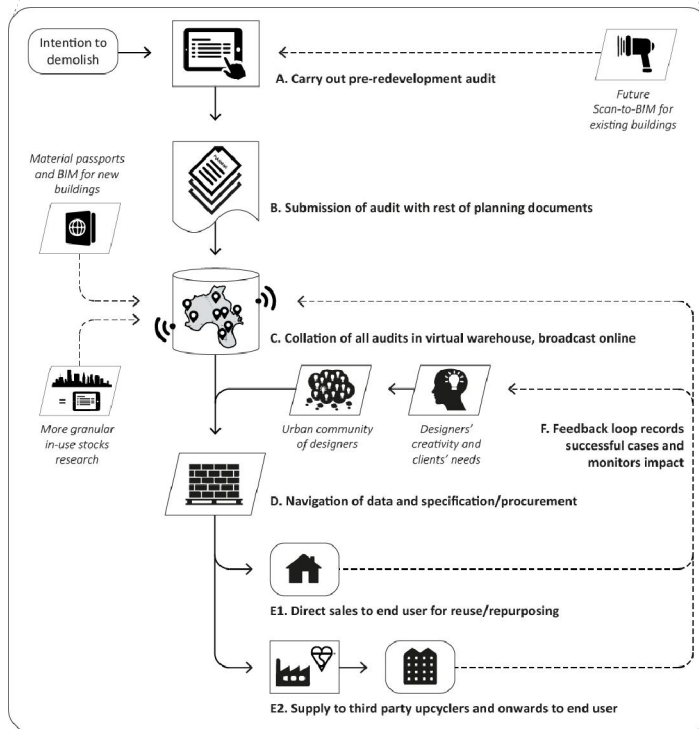
Systems engineering diagram for urban-level component management
(Figure 19)

Triage intervention system at its centre



Triage intervention system process diagram
(Figure 13)

E-BAMB database related activities filled in grey



E-BAMB information system flow diagram
(Figure 14)

Database at its centre; detailed explanation of information flows and additional future inputs

Figure 20: Overview of nested arrangement of component management, triage and E-BAMB systems diagrams

5.4 Applying the triage intervention system

5.4.1 Introduction and research objectives

Since section 5.2 (Rose and Stegemann, 2018b) recognised that: ‘Until the information and infrastructure to support reuse exists, it is hard to establish the extent to which it would benefit industry; and until real benefits are proven, it is hard to justify investment in the types of innovation described in this section’, this section aims to explore this gap in knowledge. To what extent might reuse, repurposing and upcycling ideas emerge, and be realised, if a portion of the demand side of the market is exposed to a portion of E-BAMB information? The objectives are to:

- Examine the effectiveness of aspects of the intervention system described in sections 4.2 and 5.2 through a series of short live case study projects;
- Test the principle that reuse, repurposing and upcycling ideas emerge when E-BAMB information is available;
- Discuss means of sustaining the proposed system at the scale of a housing organisation.

5.4.2 Methods used to test the triage intervention system

Multiple case study

The triage intervention system has many mutually supportive elements, and to implement it would require resources and capacities well beyond the scope of a doctoral project. A much-simplified model of the triage is deployed in these live case studies, focusing primarily on the provision of E-BAMB information. The term ‘live’ is used here to mean case studies that are not only observational, but involve an action element, in the sense of facilitating material exchanges, physically making and testing material processes, and actively engaging with architects’ design processes.

The format for all of the case studies is the fostering of connections between a large construction or demolition project, which acts as a supply of end-of-use components, and a cluster of smaller, local projects, which are the potential recipients (Figure 8). In some cases, fruitful connections led to the realisation of reuse, repurposing and upcycling processes, while in others, impediments prevented any exchange from taking place. It is not the intention of this section of the thesis to provide comprehensive accounts of events within each case study project, but to run through a number of them, picking out salient points that contribute to the analysis of the triage in use. Instances of both success and failure are discussed.

With one exception, the projects were led by or connected to the operations of the industrial sponsors. The recipient projects range from a temporary 'Parklet' for community engagement, to the permanent fit-out of a co-working space. All were of relatively short construction timeframes compared to Poplar HARCA's major construction projects. The case study data collection was thus closer to cross-sectional 'snapshots' than the longitudinal form of case studies described in section 4.2.

Triage activities

The activities undertaken with recipient demand side projects are summarised in Table 16. Early identification of the components to emerge from forthcoming soft strip or demolition was achieved through photographic surveys and sorting of photographs into component types based on the Common Arrangement of Work Sections (e.g., K20 timber flooring; L10 windows; CPIC, 1998). Information was shared with selected local enterprises and architects working on projects nearby. Their needs represented demand, and their creativity was exercised in identifying ways to meet that demand with the available components. Design proposals that involved a level of component processing, rather than direct reuse, were executed by a mix of small businesses and individuals, along with the researcher. This began to form a local network with capacity for reclamation, reverse logistics and remaking.

Role of the researcher

The researcher acted as a conduit for information on availability of materials from contractors undertaking demolition and new build projects for the industrial sponsors, to architects undertaking other building projects nearby. Once an interest was established, the researcher facilitated design discussions with architects by providing qualitative descriptions of the components under consideration (e.g., through photos and comments on condition), alongside detailed survey of sizes and quantities. The information offered was intended to permit the possibility of reuse, without determining its form. Ideas emerged from and were developed by the architects rather than the researcher.

Reporting of case study observations as 'feedback loop'

As described in section 5.2.4, the proposed E-BAMB information system is designed with a feedback loop that measures its own impact by recording waste prevention, avoided primary material purchasing, and embodied carbon savings. It also records successful instances of repurposing, so that the creative act of transferring from an original to a new use is codified in the database for future users. This is taken as a loose framework for reporting the observations from case study projects, which considers:

- Reuse, repurposing and upcycling idea generation based on E-BAMB information;
- Realisation of reuse, repurposing and upcycling;

- Quantities of items reclaimed and diverted from waste stream;
- Avoided primary material purchasing and associated environmental impacts;
- Additional local employment, growth in reuse capacity and new working relationships;
- Resources required to support the application of triage processes.

In the following subsections, case study findings under these points are recounted against the triage activities listed in Table 16. They are grouped by their ‘parent’ supply project.

Table 16: Triage activities undertaken in collaboration with recipient projects, listed by ‘parent’ supply project

Triage activity (From Figure 6 in Rose and Stegemann, 2018a)	Deployed version of activity	Leader of activity (key below)	St Paul’s Way	Aberfeldy Village Phase 3	Aberfeldy Village marketing suite	Keys House/ Dorset House
Audit	Photographic inventory	R	x	x	x	x
Submission and collation	Applies only when gathering data from many projects	-				
Broadcast data	Inventory shared by email	R	x	x	x	x
Marketing	No public exposure or promotion	-				
Navigate data	Inspect inventory, discussion	P	x	x	x	x
Integrate in design	Integrate in design, workshops	P	x	x		x
Facilitate procurement	Facilitate free exchange	R	x	x	x	
Reclamation	Reclamation from soft strip	I, P	x	x	x	
Consolidation	Storage prior to processing	I	x	x	x	
Product design	Upcycled and repurposed product design	P, R	x			x
Material processing and testing	Upcycling and repurposing processes	I, P, R	x	x		
Recertification	Not achieved	-				
Sales	Upcycled and repurposed product sales	I, R	x			
Reuse	Reuse	P	x	x	x	
Feedback loop	Successes recorded in following sections	R	x	x	x	

Abbreviations: I = intermediary; P = demand project participant; R = researcher.

5.4.3 St Paul's Way: Linton and Printon House, St Paul's Way School and Burdett Mosque

St Paul's Way is an extensive development by Poplar HARCA, including the demolition of Linton and Printon House (five- and six-storey concrete-framed buildings from the latter half of the twentieth century; Figure 21 and Figure 22), primary school buildings and a mosque; to be replaced by construction of new housing, school buildings, and a new mosque.

The different stages of demolition and construction afforded different opportunities to foster connections with potential demand projects. The first of these, Chrisp Street Exchange (CSE), was the project that allowed the greatest coverage of triage activities (Table 17).



Figure 21: Linton House, St Paul's Way elevation



Figure 22: Printon House, St Paul's Way elevation

Chrisp Street Exchange

CSE was a Poplar HARCA project, but unlike the major housing projects run by the Development and Regeneration Team, this was a modest fit-out of a derelict retail unit to create a new co-working space. Poplar HARCA's Accents Team (Arts and Culture, Community, Enterprise, Sustainability) were the client and project managers. Architects Seán and Stephen Ltd were appointed to design the fit-out.¹

¹ seanandstephen.com/projects/chrisp-street-exchange; poplarharca.co.uk/chrisp-street-exchange

Table 17: Triage activities undertaken for St Paul's Way → Chrisp Street Exchange case study

Triage activity	Deployed version of activity	Leader of activity	Description of actions undertaken
Audit	Photographic inventory	R	Researcher surveyed Linton and Printon House flats, maisonettes and stair cores and other common areas for components that could be removed in soft strip. Photographic inventory as Figure 23, with components categorised using the Common Arrangement of Work Sections (CPIC, 1998).
Broadcast data	Shared by email	R	Emailed inventory to architects.
Navigate data	Inspect inventory, discussion	P	Meeting with architects; they narrowed down to a few possible reuse options; for those items, researcher ascertained available quantities, dimensional info, confirmed removability.
Integrate in design	Integrate in design, workshops	P, R	Architect developed drawings of three elements of the fit-out using timber floorboards and steel meter cabinets, based on survey information. Researcher produced a sample of the processing of timber and of meter cabinet as locker frontage.
Facilitate procurement	Facilitate procurement	I, R	Tender drawings costed by intermediary third parties and researcher; contract agreed to deliver locker units, 'banqueting table' and timber for reception desk panelling.
Reclamation	Reclamation from soft strip	I, P	Reclamation of floorboards and meter cabinets carried out prior to demolition and without connection to demolition contractor. Timber reclamation contractor agreed method statement with Poplar HARCA and new build contractor. 25 m ² of floorboards reclaimed from one maisonette. 21 no. meter cabinets reclaimed by researcher and assistant from 21 flats/maisonettes.
Consolidation	Storage prior to processing	I	Timber transported to RBL and stored ready for processing. Meter cabinets delivered to CWS and stored until locker carcasses had been prepared.
Product design	Upcycled and repurposed product design	P, R	Architect's design intent drawings translated into manufacturing processes and detailed procurement list (e.g., fixings, biscuit joints, adhesives).
Material processing and testing	Upcycling and repurposing processes	I, P, R	Meter cabinets repurposed as the frontages of lockers in two banks of ten; locker carcasses made from reclaimed scaffolding boards by CWS (Figure 24). Banqueting table timber planed, thickened and trimmed at RBL; jointed to form lamellae and pressed into two CLT panels (Appendix R); joined into one long table on site (Figure 25). Reception desk timber planed one side and trimmed ready for reuse.
Sales	Upcycled and repurposed product sales	I, R	Contract sum covered all costs of processes, and with the exception of some voluntary time, all work was paid at a pre-agreed price or a rate above minimum wage.
Reuse	Reuse	P	Furniture items were installed. Reception desk timber was mitred and fitted as panelling in situ. All are in use.
Feedback loop	Thesis section 5.4	R	Meter cabinets can be removed intact and repurposed as doors with simple tools and little skill. Reclaimed timber can be upcycled to make panels that could serve structural purpose; in this case non-strength graded floorboards were used for non-structural furniture application. New aluminium or steel lockers and new table top of unknown material were displaced.

Abbreviations: CLT = cross-laminated timber; CWS = City Wood Services; I = intermediary; P = demand project participant; R = researcher; RBL = Remakery Brixton Ltd.

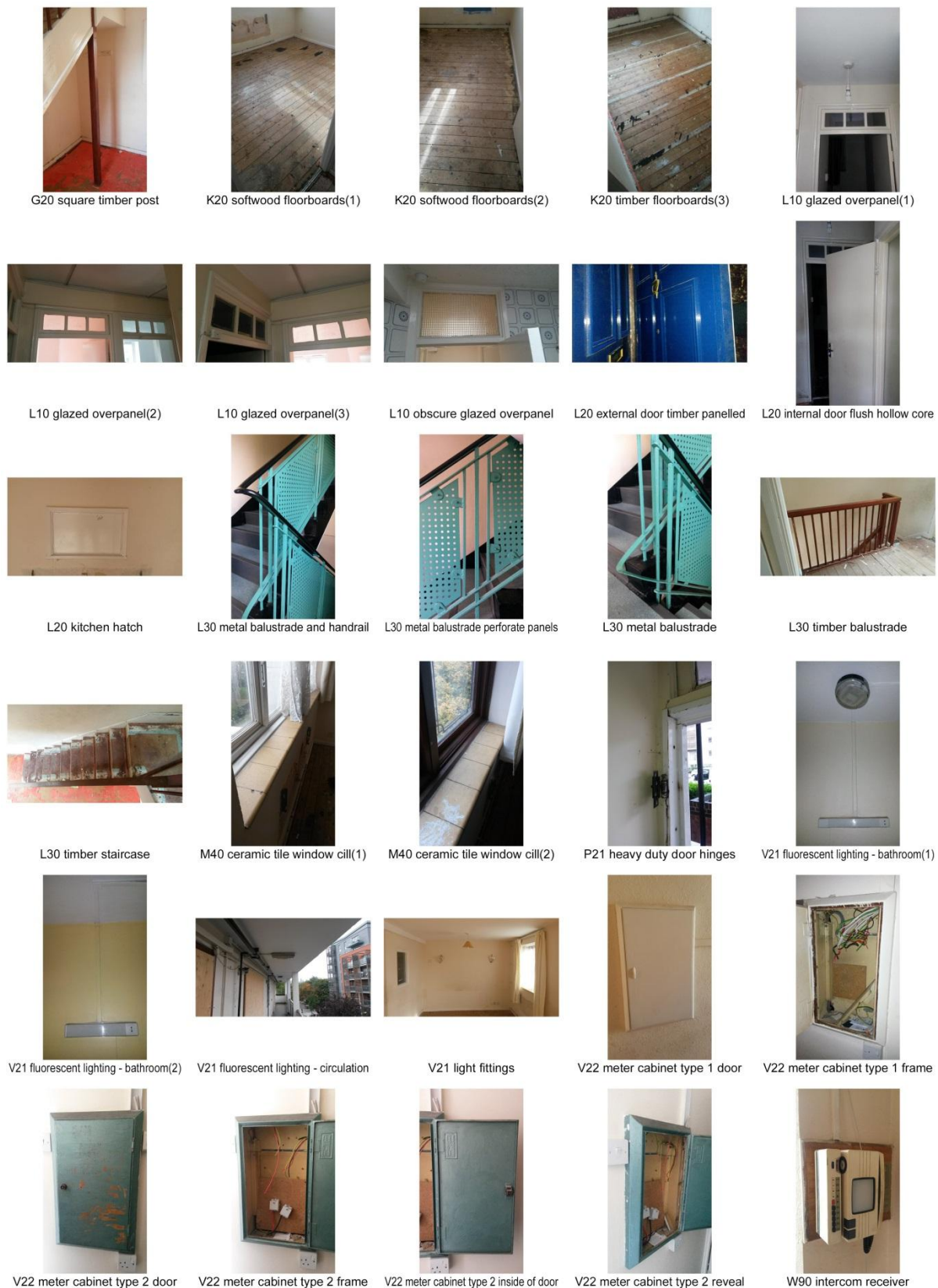


Figure 23: Audit of Linton and Printon House, St Paul's Way – photographic inventory of components that could potentially be removed in a soft strip, categorised by component type according to the Common Arrangement of Work Sections (CPIC, 1998), i.e. industry-wide specification clauses that are familiar to practitioners.



Figure 24: Triage material processes undertaken to repurpose meter cabinets as lockers for Chrisp Street Exchange.



Figure 25: Triage material processes undertaken to upcycle floorboards as banqueting table for Chrisp Street Exchange (image for public engagement at Victoria & Albert Museum *Friday Late*, 2016).

The CSE project framework provided a better-than-usual context for considering alternative approaches to procurement. Poplar HARCA's Accents Team was keen to trial aspects of the research project; their pre-appointment brief for architects referred to collaboration with UCL on reuse. The chosen architects had no specific prior impulse to include reuse in their work but were enthusiastic about procuring elements of the fit-out through means other than normal

specification. They had a measured degree of caution over the ability to deliver to site completed products of the required quality, but assurance was provided through initial samples, a small mock-up before full size fabrication of the table panels, and photos of work in progress. Working with a smaller main contractor and less established architects meant that the team's approach was less rigidly procedural.

Nevertheless, if the meter cabinets had simply been delivered to site with only an architect's design intent drawings, the locker units would have been far less likely to succeed. The off-site storage and place of production provided by City Wood Services (CWS) was important. It took the non-standard procedures away from the construction site, so that installation was no more onerous than it would have been for new products. To make the floorboards reclaimed from Linton and Printon House suitable for new use required minor or major transformation. The reception desk timber was planed on one side, trimmed, wiped down, and stored at the Remakery (RBL) until it was needed on site. The workshop space, machinery and people at RBL allowed an experimental use of secondary timber to be tested and carried out successfully, without any unusual impact on site.

The three secondary elements – reception panelling, lockers and banqueting table, demonstrating reuse, repurposing and upcycling – indicate emergence of ideas even where the potential supply looked unpromising. None of the materials would be reclaimed for salvage; their value is too low and demand too uncertain. Their transformation had to add enough value to justify the costs of processing, which in this case it did. A major systemic change from the salvage yard scenario was that specific demand-pull was made visible to actors on the supply side, so the risk of reclaiming and storing goods that do not sell was minimised. The sale of repurposed and upcycled products (as opposed to giveaway of 'second-hand' goods) and the craft and consideration that sometimes goes into the process, may result in them being more highly prized and likely to have a longer lifespan.

In this case the process led from:

- E-BAMB information → to architect's project needs → discussion of possible materials and ways to meet them → specific ideas → intermediary undertakes production;

i.e., the intermediary was involved in the design process. This was a somewhat artificial situation, in that the researcher was providing capacity to instigate all triage activities; the model could not reproduce at industry-wide scale. In practice, the process could instead lead from:

- E-BAMB information → directly to a designer's specific ideas → they find reuse specialists in a local network able to carry out production.

This bespoke pattern of procurement provokes an image of a small-scale, entrepreneurial and potentially craft-based, distributed supply chain. Such a supply chain is likely to produce a

smaller quantity of higher margin components, like the furniture for CSE. A further alternative is that the process leads from:

- E-BAMB information → to manufacturer with established or new process → harvest of materials from a series of sites → continuous production → products marketed to designers.

This is a pattern more akin to current mass manufacturing, and is likely to produce a larger quantity of lower margin components. It may be able to displace a larger quantity of primary production and improve upon or delay the impacts of waste management. The potential to expand the production of cross-laminated timber (CLT) panels as an upcycling enterprise in this pattern is considered in Chapter 6, where the material processing aspects of the product are described in more detail.

Parklet, Poplar Pavilion, Tommy Flowers Pub and Kafe 1788

The new buildings for St Paul's Way Foundation Primary School were built using CLT from an Austrian producer. This provided the opportunity to witness installation of CLT at first-hand. It is often described as a construction technique that creates no site waste, but the Poplar HARCA project manager had observed surplus CLT 'offcuts'. These were not cut on site, but were factory offcuts used as packing materials, along with softwood boards, to avoid damage in transit. The project manager also flagged up a last-minute opportunity to intervene in the soft strip of items from the former mosque building.

The potential recipient projects for these materials had lesser requirements than CSE. Parklet was a small planter and street furniture installation, built and used in one week as a platform for community engagement by the architecture charity, AzuKo.² Poplar Pavilion was a much larger exercise in engagement and place-making, but also temporary, instigated by artist and Wellcome Trust Public Engagement Fellow, Alex Julyan.³ The Tommy Flowers Pub is a new venue near Poplar HARCA's Aberfeldy Village development. Kafe 1788 is an enterprise that has become established since moving into an empty retail unit made available through Poplar HARCA's Open Poplar scheme.⁴ Table 18 summarises the triage activities undertaken in recirculating components from St Paul's Way to these projects.

² azuko.org/

³ alexjulyan.com/front.php

⁴ openpoplar.com/space/; kafe1788.com/

Table 18: Triage activities undertaken for St Paul's Way → Parklet, Poplar Pavilion, Tommy Flowers Pub and Kafe 1788

Triage activity	Deployed version of activity	Leader of activity	Description of actions undertaken
Audit	Photographic inventory	R	Researcher photographed packing materials (softwood boards and factory CLT offcuts used in transportation of CLT panels) and straps used for craning panels into place. No early identification of materials from mosque.
Broadcast data	Shared by email	R	Emailed photographs to architects of Parklet and founders of TFP.
Navigate data	Inspect inventory	P	Parklet and TFP teams established what they could use without further discussion.
Facilitate procurement	Facilitate free exchange	R	Researcher made contact between contractor and Parklet/TFP teams, and between PP artist and PH project manager.
Reclamation	Put to one side for collection; soft strip	P	Loose packing materials stored on site for short period before collection by recipients. Radiator covers soft stripped from mosque by PP team.
Consolidation	Storage prior to processing	I	PH made empty garage space available for storage of timber for Parklet.
Product design	Repurposed product design	P	Parklet and PP had loose design intent, which developed in hand-to-mouth way once materials were available.
Material processing and testing	Upcycling and repurposing processes	P	CLT offcuts repurposed as benches spanning onto stacks of softwood packers, and longer lengths of softwood used to make triangular seating (Figure 26a). Radiator covers repurposed as flooring in PP (Figure 26c).
Reuse	Reuse	P	Items installed for Parklet, PP and TFP. Short-term use of benches in Parklet, then moved to Kafe 1788, where they continue to be in use (Figure 26b). Other Parklet seating stored by PH for potential reuse in Fashioning Poplar project.
Feedback loop	Thesis section 5.4	R	New CLT may be packed with timber that can very simply be repurposed to displace new café/pub furniture. Several cubic metres bulk volume of timber diverted from waste management, with little production wastage in repurposing.

Abbreviations: CLT = cross-laminated timber; I = intermediary; P = demand project participant; PH = Poplar HARCA; PP = Poplar Pavilion; R = researcher; TFP = Tommy Flowers Pub.



Figure 26: (a) Parklet temporary street furniture from timber packers (photo: Nathan Ardaiz); (b) Parklet bench from CLT offcut reused in Kafe 1788 (photo: Alejandro Romero Perez De Tudela); (c) radiator covers as flooring in Poplar Pavilion.

The school building contractor was happy to put to one side materials for reuse and allow collection. Diverting reusable goods away from waste management was very straightforward, and the contractor's waste disposal costs were slightly reduced. Poplar HARCA typically has empty garages and other small spaces available, which provided useful temporary material storage to facilitate reuse. Unlike demolition waste, the packing materials could not be anticipated in advance, so the projects that were able to benefit were those that could make use of almost any quantity, without strong preconceived ideas of what materials they planned to use. After providing initial photographs of available components, ideas for how to repurpose them to meet the needs of the recipient projects were generated without the researcher's intervention. In the case of use of materials from the mosque soft strip, the researcher's only action (besides raising awareness that reuse is a possibility to be encouraged, through the research project's existence), was to put the Poplar Pavilion team in touch with Poplar HARCA's project manager at the right time.

Short-term use of timber for temporary projects may produce only minimal positive impacts. To counteract furniture being discarded after a limited period of use, follow-on uses were arranged for the benches, and the triangular seating was made with a reversible process so that the timber could be recovered if the seating is not needed. Unfortunately, most of the materials from Poplar Pavilion were scrapped after five months' use.

5.4.4 Aberfeldy Village Phase 3

Aberfeldy Village is a phased development involving the demolition of eighteen mid-twentieth century housing blocks and regeneration of the estate over the course of almost ten years. Phase 3 included demolition of seven of these buildings.

In this case study, audits of the existing buildings were shared with a selection of architects and local enterprises, rather than being targeted at one project only, as was the case with CSE. The reclamation was coordinated with the developer in parallel with their soft strip, rather than being carried out by third parties independently of the main site operations (Table 19).

Fashioning Poplar, Mobile Garden City and Pro Bike Service

Like CSE, Fashioning Poplar is a project led by Poplar HARCA's Accents Team. However, it is a much larger project in collaboration with the London College of Fashion, part-funded by the Greater London Authority (GLA), comprising significant new build elements as well as adaptation of 81 garage units, external public space and a community garden. Architects Adams & Sutherland were appointed.⁵

⁵ www.adams-sutherland.co.uk/projects/fashioning-poplar/; www.poplarharca.co.uk/fashioningpoplar

Mobile Garden City is a collaboration between Groundwork London, architects Public Works and Local Energy Adventure Partnership, who design and install micro anaerobic digesters.⁶ From its base on the Queen Elizabeth Olympic Park, part of the garden and the anaerobic digester moved to a site in Poplar.

Pro Bike Service is a start-up project for bicycle servicing and training.⁷ Its founder designed and implemented the fit-out of a shipping container to make a transportable bicycle workshop. Initially it was co-located with the Mobile Garden City and has now moved to another part of the Queen Elizabeth Olympic Park.

Table 19: Triage activities undertaken for Aberfeldy Village Phase 3 → Fashioning Poplar, Mobile Garden City and Pro Bike Service case study

Triage activity	Deployed version of activity	Leader of activity	Description of actions undertaken
Audit	Photographic inventory	R	Researcher surveyed three typical buildings with a focus on components that could be removed in soft strip.
Broadcast data	Shared by email	R	Photographic inventory to emailed to FP, MGC and PBS teams, and PH Accents Team for further distribution to network.
Navigate data	Inspect inventory	P	MGC and PBS established what they could use without further discussion; FP team could not find components to meet needs.
Facilitate procurement	Facilitate free exchange	R	Researcher made contact between developer and MGC/PBS teams.
Reclamation	Reclamation from soft strip	P	Developer arranged for 50 linear metres of fencing panels to be carefully removed and set to one side for MGC to collect. PBS attended site and worked alongside contractors to reclaim steel kickplates and piano hinges from 10 no. external doors, 6 no. aluminium signage sheets and 5 no. plywood boards.
Consolidation	Storage prior to processing	I	PH made empty garage space available for storage of fencing for MGC.
Product design	Repurposed fit-out design	P	PBS shipping container fit-out design required plywood and hinges; design altered to accommodate aluminium and steel.
Material processing and testing	Repurposing processes	P	Plywood and hinges cut to size and used to make built-in cabinets; aluminium repurposed as work surfaces and reused as external signage; steel kickplates mounted on wall with bike brackets to protect wall finish from damage (Figure 27).
Reuse	Reuse	P	Fencing panels intended for reuse as boundary for new site but remain in storage awaiting reuse. PBS items in use.
Feedback loop	Thesis section 5.4	R	Sheet metal can provide hardwearing surfaces to lengthen other elements' lifespans. Any working hinge is useful and can displace new production. Both could command a sale price if the right users are found.

Abbreviations: FP = Fashioning Poplar; I = intermediary; P = demand project participant; MGC = Mobile Garden City; PBS = Pro Bike Service; PH = Poplar HARCA; R = researcher.

⁶ www.groundwork.org.uk/Sites/london/pages/mobile-garden-city ; <https://r-urban-wick.net/communitybydesign.co.uk>

⁷ <https://probikeservice.co.uk/>



Figure 27: (a) Pro Bike Services' converted shipping container; (b) plywood cabinetry; (c) aluminium sheet lining to work surfaces (photos: Lawrence Mohammed).

Taking piano hinges off doors is a level of reclamation that would not normally be considered worthy of the time by a contractor; but, when exposed to a suitable audience, the value was recognised and retained, rather than being sent for scrap. In buildings that in general are not made of good quality salvageable components, the doors and door furniture are notable exceptions. The quantities of reclaimed materials were very small in the scale of estate regeneration, but a significant harvest for a new enterprise working on a shoestring. PBS was the model small-scale recipient project, thanks to the founder also being the designer, funding the project, and doing the reclamation and remaking himself. He was well-equipped with tools and had the practical skills to execute the project well.

The ambition for reuse in Fashioning Poplar was that it should be a step up in scale and accomplishment from CSE. The project framework appeared promising: architects with a prior interest in reuse, a cultural project, and a tight budget that would benefit from low-cost materials. At the time of this case study, the project had wider issues regarding the matching of scope and budget, and progress was delayed. The effect of budgetary constraints was to force every element to be as cheap as possible, e.g., a rubber external wall cladding was found at £6/m². Separately, used tyres had been salvaged for use as an acoustic barrier between garden and main road, and the idea of using rubber from the wearing surface of tyres for the cladding was discussed. However, material prices are too low for this first-time, innovative product to be competitive; even if the source material is free, or the upcycler is paid to take it, they could not be confident of getting close to matching the price of the new product. (This is before performance and certification issues are considered.) Other benefits of the upcycled product, such as local employment and carbon savings, did not enter the equation.

The Accents Team project manager noted that elsewhere in the budget, there is an allowance for off-site renewable energy generation to meet the GLA's zero carbon policy. Alternatively, they may choose to pay a levy per tonne of non-avoided operational carbon emissions. The policy attempts to internalise a negative externality: it adds value to the inclusion of renewable energy generation by making its absence a cost, and in doing so has helped to create a

burgeoning industry in photovoltaics. This apparent success suggests there may be opportunities for incentivising other approaches to carbon offsetting. With sufficient data, savings in embodied carbon that improve on an agreed benchmark have been suggested as an 'allowable solution' to meeting the zero carbon targets (Battle et al., 2014). In the context of Fashioning Poplar, the carbon benefit of a local, secondary material would thus be monetised by its ability to reduce the levy payable. The value of the reused product would thus increase and the economic case for starting to produce it would improve. The London Legacy Development Corporation (LLDC) have begun to make steps in this direction, by providing funding from received carbon levy payments to projects that achieve carbon offset through embodied carbon improvements (LLDC, 2016).

5.4.5 Aberfeldy Village marketing suite

The marketing suite for properties in the new Aberfeldy Village was accommodated in the ground floor of one of the housing blocks. When the developer was preparing to convert the area into apartments, they made Poplar HARCA's Development and Regeneration Team aware of the forthcoming removal of fit-out items. They were aware of Poplar HARCA's 'team that upcycles such items' and asked to be put in touch. The enquiry was forwarded to the researcher and a visit was arranged to audit the marketing suite. It had been in use for only five years and included reception furniture, office furniture, kitchen units, track lighting and light fittings, glazed partitions and sanitaryware (Table 20).

Tommy Flowers Pub, Kafe 1788, Pro Bike Service, Mobile Garden City, The Tramperry/Fashioning Poplar, Trinity Buoy Wharf, George Green office

The developer wished to make items available free of charge to charities, or failing that, to local businesses for a small donation. As well as suggesting links to the local charitable sector, the audit information was circulated to a growing list of local projects and start-ups. These are not described individually but included many of those involved in the case studies reported above, as well as The Tramperry, a workspace provider for entrepreneurs involved in the Fashioning Poplar project, with a space in Poplar where items could be used until Fashioning Poplar is ready; the artists' studios at Trinity Buoy Wharf; and Poplar HARCA's own new office space, George Green.

A five year old marketing suite is far from typical C&D waste. However, the case showed that the process of redistributing reusable goods does not have to be longwinded. The period from the first contact made by the developer to the collection of items was less than three weeks. The only items not to find a new home were a large and cumbersome reception desk; a floor-to-ceiling glazed partitioning system; and kitchen units and worktop that were damaged in removal. The process required the resource of the researcher (or someone else) to visit and audit available items, share photographs with a network, gather responses and make contact between supply project and recipients. It required the developer to be aware of the reuse

network and be willing to coordinate collections. The input of resources on both sides was minimal, and would be outweighed by the value of reused goods and avoided waste disposal costs.

Table 20: Triage activities undertaken for Aberfeldy Village marketing suite → local projects and start-ups case study

Triage activity	Deployed version of activity	Leader of activity	Description of actions undertaken
Audit	Photographic inventory	R	Researcher made photographic inventory of all items not already committed to charities by the developer.
Broadcast data	Shared by email	R	Emailed inventory to network on first come, first served basis; forwarded to others (with permission) to increase reach.
Navigate data	Inspect inventory	P	Most placed their requests based on inventory; TFP made a visit.
Facilitate procurement	Facilitate free exchange	I, R	Researcher gathered responses from network; developer produced a spreadsheet to allocate items; researcher shared contact details and developer coordinated collections.
Reclamation	Reclamation from soft strip	I, P	Some items were loose fittings and furniture; reclamation of fitted items like track lighting was organised by developer.
Consolidation	Storage prior to reuse	P	PH stored office chairs prior to use at George Green office.
Reuse	Reuse	P	All direct reuse rather than repurposing/upcycling. Items redistributed to five different organisations, largely in use.
Feedback loop	Thesis section 5.4	R	Total avoided waste included >50 m tracklighting, >35 no. light fittings, 2 no. bathroom suites, 4 no. office cupboards, a meeting table and 8 no. meeting room chairs, 3 no. office chairs, 3 no. coffee tables, a sofa, an armchair and a chrome bench. Some used only because it was available for free, but some displaced procurement of equivalent new products.

Abbreviations: I = intermediary; P = demand project participant; PH = Poplar HARCA; R = researcher; TFP = Tommy Flowers Pub.

5.4.6 Keys House and Dorset House

The researcher was approached by a contractor that was aware of the research project through engagement on Tower Hamlets Homes's Decent Homes programme. The contractor was tendering for a job that would involve the removal of around 3,600 m² of high pressure laminate cladding panels and external wall insulation from two twelve-storey tower blocks in Enfield. The towers had been upgraded only a few years earlier, but the insulation was failing. Removing it would lead to a vast quantity of materials, which the contractor was hoping could be redistributed to charities or social enterprises. The information was forwarded to some of the larger projects around Poplar, and to two architectural practices known to the researcher.

One of these practices, Reed Watts, was working on their entry to a design ideas competition run by the housing charity, Commonweal Housing.⁸ The brief called for the design of temporary housing units that could be deployed inside existing buildings, for vulnerable migrant workers who would otherwise be homeless. The architects decided to base their proposal around repurposing cladding from the tower blocks (Table 21).

Table 21: Triage activities undertaken for Keys House and Dorset House → Commonweal Housing case study

Triage activity	Deployed version of activity	Leader of activity	Description of actions undertaken
Audit	Site photographs and measure	C	Contractor provided general photographs of tower facades and estimated total quantity of cladding panels.
Broadcast data	Shared by email	R	Researcher forwarded contractor's information to architects.
Navigate data	Inspect inventory, discussion	P	Meeting with architects; they decided feasible to proceed with design proposal using panels; requested detailed information. Researcher provided elevations based on contractor's photos and online search for panel size information (Figure 28); and spreadsheet inventory of panel sizes and colours.
Integrate in design	Integrate in design, workshops	P, R	Architect developed design based on survey information. Researcher attempted to confirm removability of panels.
Product design	Upcycled and repurposed product design	P, R	Proposal developed into kit of parts for modular dwelling unit. Designed to repurpose panels with the minimum of cuts; simple reversible jointing to allow units to be dismantled and reconstructed multiple times in different buildings.

Abbreviations: C = supply project contractor; P = demand project participant; R = researcher.

Reed Watts' entry won the competition and the client was keen for a prototype to be fabricated. The contractor's original enquiry preceded the 2017 fire at Grenfell Tower in London. Although the panels at Keys House and Dorset House were non-flammable, and the problems unrelated to those of the cladding at Grenfell Tower, the council requested immediate removal of the cladding as emergency works. This removed the time that the contractor could have used for planning a process of careful dismantling.

The contractor also reported that their health and safety advisors would not allow panels to be removed as complete components. A pest infestation had created a 'shock' risk: a pigeon could suddenly fly out from behind a panel, shocking the worker, and potentially causing them to spring backwards and fall from the scaffolding. The health and safety advice was that the risk is minimised by removing panels in parts rather than as a whole (rather than by using an enclosed form of scaffolding from which workers could not fall). This seems a spurious reason; perhaps it was a cover for the perceived cost penalty of removing complete panels. The contractor was

⁸ <https://www.commonwealhousing.org.uk/>; <http://www.reedwatts.com/starter-for-10-flat-pack-shelters/>

not able to demonstrate that their commercial team had analysed the total cost of disposal, and compared that to the cost of dismantling and resale.

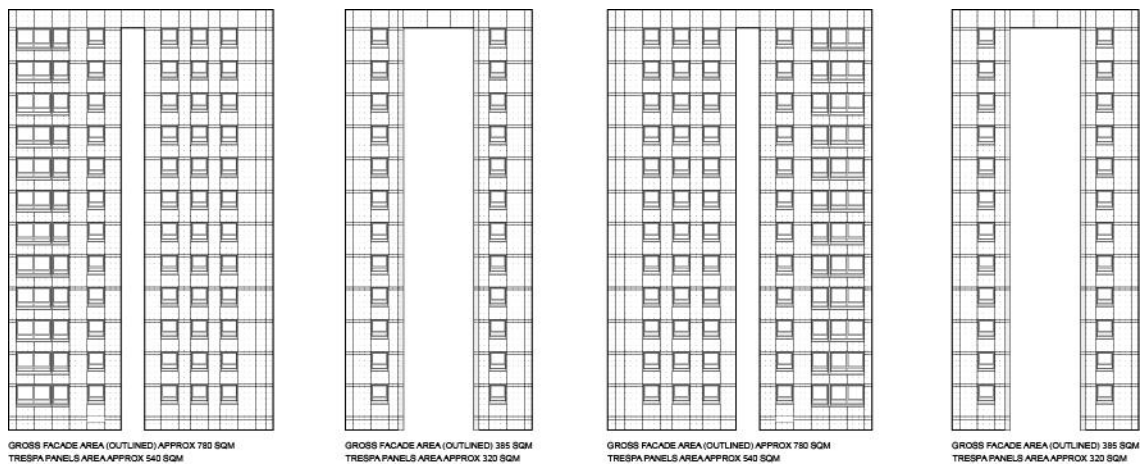


Figure 28: Survey elevations of Keys House/Dorset House high pressure laminate cladding panels.

As the contractor was tendering at the time of first contact, it is likely that they wanted to present a positive approach towards waste management in their bid. Once the job was won, their conviction in carrying out the proposed reclamation did not match the initial enthusiasm. It is positive that the contractor acted upon early identification of reusable components and broadcast their 'audit' to seek possible recipients. In the full deployment of the triage process, however, it is important that the incentive to supply is not placed only on providing information, but also on achieving actual waste prevention or carbon savings. This will require the endorsement of contractors' health and safety, commercial and operations teams, not only the sustainability team as appears to have happened in this case.

5.4.7 Discussion of live case study findings and limitations

Type of audit information

Collaboration with architects provided insights into their informational needs and practices in relation to reuse. A photographic inventory was found to be an efficient way to gather and present audit information that architects and others could use, along with a broad idea of quantities. This was supplemented with further qualitative and quantitative information where requested. In the live case study projects information was shared: at first, with only one potential recipient project, and later with several. This was manageable, given that there was usually only one supply project at a time, and given the focus on a limited number of local recipient projects. As the flows of information grow larger, the introduction of an E-BAMB database – a virtual warehouse – would become increasingly beneficial. Section 5.2 discusses its role within the industry at large, but a simple database could be viable within housing organisations like Poplar HARCA or Tower Hamlets Homes. Local businesses, community

groups and the design teams of all the organisation's projects could be given access to the virtual warehouse.

Emergence of reuse, repurposing and upcycling ideas

One of the arguments put forward in section 5.2 is that widespread sharing of information would yield a wealth of ideas from the broad creative faculties within and around the industry. This cannot truly be substantiated without putting into place the requirement to submit audits at planning stage, collating E-BAMB information from a wide range of projects, organising and promoting the E-BAMB database to potential demand, and observing reactions. Nevertheless, in the private and semi-private spheres in which the case studies were set, many ideas did emerge, and a significant proportion were implemented, including examples of repurposing and upcycling as well as direct reuse of components.

Types of secondary use achieved in the live case studies

Some of the recipient projects in the case studies were able to make use of secondary components without any certainty over quality or quantity available; this meant that direct reuse was possible in a number of cases. There were also recipient projects, such as CSE, that did have stipulations about the level of quality that would be suitable, and specific quantities to meet the project's needs. In that case, the requirements were met through intermediaries carrying out repurposing and upcycling processes. The two modes of recirculation – i.e., with or without intermediaries – both play a part in a system of component management. Even in a future with a mature infrastructure of upcycling and repurposing businesses, connecting networks of smaller and less demanding recipient projects into the triage would be of benefit to those projects, and to the system's efficiency. Projects like Pro Bike Service help by making use of minor waste streams that are overlooked by others. Although individually they are small, if many enterprises were enabled to work in the manner of Pro Bike Service, they would begin to have a significant impact, and a greater number of nodes and connections in a network would increase the likelihood of any given opportunity being taken.

Local employment and reuse capacity

The live case studies brought together various individuals and enterprises in new working relationships. For instance, the lockers and table supplied to CSE actively involved eighteen people, from the client who commissioned the work through to the site manager with whom installation was coordinated. This included local spending on semi-skilled and skilled work, retaining Poplar HARCA's money in the local economy. The incorporation of reuse, repurposing or upcycling in a project calls upon capacity for reclamation, material handling and transportation, places to store and process materials, equipment and skills in working with materials. For CSE, the researcher was able to draw upon a timber reclamation contractor known to Poplar HARCA, and upon City Wood Services and the Remakery for space,

equipment and people with reuse and carpentry skills. There was also some voluntary assistance with reclamation, material handling and transportation from a member of Poplar HARCA staff and a student from UCL. The case suggests that capacity does exist to carry out such processes at small scale, but it is poorly coordinated at present. The researcher pulled together resources, mostly from small, independent organisations, and the processes of reclamation and reuse were carried out separately from the main contractor's and subcontractors' site operations.

Later, at Aberfeldy Village, the timing of reclamation was integrated into the main contract period, and some of the reclamation was carried out or assisted by site workers. Reclamation being integrated into normal site activity is a positive development that may help to normalise the process and build capacity. However, it still required the researcher to drive the process up to that point, and mediate between supply and demand. A 'minimum viable' triage to replace the researcher and enable component recirculation in housing organisations like the industrial sponsors is considered next.

Sustaining the triage at the scale of a housing organisation

Poplar HARCA have a housing stock of over 9,000 properties, and carry out a significant amount of demolition and redevelopment; Tower Hamlets Homes manage around 22,000 properties, and run responsive and cyclical maintenance programmes, and occasionally new build projects. The case studies have demonstrated that a triage can operate at this scale with some benefits. It is of particular relevance where there already exists a network of smaller local projects, community groups and new businesses that may be able to feed off unwanted components from the organisation's major projects.

Embedding the triage actions into the normal sequence of development project stages need not be resource intensive or a major change to practices for a housing organisation. A photographic audit would be carried out soon after it has been confirmed that a demolition or soft strip is to go ahead (e.g., on receiving planning consent). This would be passed on to a person with responsibility for broadcasting the audit information directly or via an E-BAMB database to the design teams of all the organisation's projects, other projects that they wish to support, local businesses and community groups. To simplify this commentary, it is assumed a database is introduced. Case study findings suggest that the information will be investigated by potential recipients and potential new uses will be considered; but a prompt may need to be built into the database to spur action. Interest from potential recipients would create an alert for supply project participants, who would have the option of opening communications. At an early stage in projects, the supply side participant may be the housing organisation or their consultants. If a request from the demand side is accepted, it could be delivered by reclamation in advance of demolition, or it could be written into tender documents. The database should link in specialist contractors, material upcyclers and stockists that can offer reclamation and reuse capacity not already present amongst the project participants.

The triage becomes more valuable as a tool for both supply projects and demand projects as its coverage grows. With increasing adoption, it becomes more likely that a demand project can find components to serve its purposes, and more likely that a supply project is able to sell useful components rather than pay for conventional waste management. These are known as network effects; the classic example is the telephone, where a growing number of users enhances the value of the technology to each user. In section 5.2, the E-BAMB information system is pitched at the scale of a local authority; the risk of implementing this system at the scale of a single organisation is that a critical mass of available materials and potential users is never reached.

If an organisation decides to facilitate reclamation and reuse of materials from their building stock, investing a certain amount of time in supporting the process is unavoidable. The feedback loop proposed in section 5.2.4 as part of an E-BAMB information system is therefore important for justifying the investment. This suggested measuring a) the financial impact on waste disposal costs and new build material costs, which, if they create savings for contractors, could come back to the housing organisation in reduced future tender prices; b) the environmental benefits of waste prevention and avoided embodied carbon emissions, which are likely to be supported by the organisation's sustainability policies; and c) the social value of free or cheap building components that not only help new enterprises establish themselves, but also create employment in recirculating materials locally. With data of this kind collected over a period of triage use, it will be possible to analyse costs and benefits and make judgements about its net value to the organisation.

Scaling up from soft strip to whole buildings

The live case studies focused largely on items that could be soft stripped, because the reclamation and reuse of such materials is within easier reach, and provided the opportunity for testing principles of the triage. The case of Keys House and Dorset House looked at the reclamation of cladding from tower blocks, but this introduced more complex challenges and ultimately was not implemented. The Poplar HARCA buildings facing demolition during the research period were not of structural types and of a scale that lent themselves to deconstruction. An exception is a current project that includes an older pub building on a site slated for redevelopment. The researcher had plans to audit the whole of the building's fabric, which would have been an opportunity to trial the triage at a larger scale. Unfortunately, the plans had to be cancelled due to repeated delays to the project.

The human resource requirements to facilitate reclamation at the scale of soft strip, such as at the Aberfeldy Village marketing suite, were acceptable to contractors and developers. At the scale of whole buildings, changes in demolition practice that make reclamation more expensive would not be absorbed by the supply side: they would need to be paid for by recipients, albeit factoring in their reduction of waste disposal costs. The price that would currently be paid for most materials emerging from most buildings would not cover this uplift. Therefore, when considering whole buildings, intermediaries who add value become critical. Removing

floorboards from Linton House by hand was certainly a more expensive process than demolition, but the process of making them into a banqueting table covered costs. If an industrial-scale process for upcycling high-pressure laminate cladding panels emerges, which allows the secondary product to command a market value, the upcycling intermediary may be able to pay a price for their feedstock that makes it worthwhile for contractors to deconstruct.

Components from the case study supply projects that presented little prospect of being reclaimed were left out of audits by the researcher. These included poor quality, cement-mortared brickwork, in situ reinforced concrete frames and foundations. In reality, for much of the time on demolition sites, these are the types of materials that can be seen. C&D waste arisings are dominated by rubble to such a degree that it becomes difficult for people to contemplate what else it might include. Other materials are also generated in vast quantities, but they appear insignificant in comparison to concrete, bricks, blockwork and excavation waste. These dense, low-value materials do not encourage the idea of waste as a reusable resource. It is arguable that (in the same way as the case studies) these materials should be excluded from the urban-level triage to focus attention on components with a greater prospect of recovery and reuse. However, the principle of opening up information to as wide an audience as possible, on the basis that unexpected ideas for reuse, repurposing and upcycling may emerge, guides away from such exclusions. Furthermore, even if reuse of these materials remains out of reach, the triage could support existing and new supply chains for recycled aggregates.

5.5 Synthesis of information system investigation and conclusions

The existing literature and the empirical investigations in section 4.2 highlighted the disconnection between two sides of a nascent market in secondary components. Section 5.2 and 5.3 explored the role of an E-BAMB information system in fomenting new connections, and showed how it could emerge from the integration of existing practical tools (e.g., pre-redevelopment audits), initiatives (e.g., RMMs) and academic fields (e.g., in-use stocks research). The generation and use of E-BAMB information needs to slot into normal building procurement processes; section 5.2 explained a theory for the importance of timely information provision. The live case studies (section 5.4) tested the theory through early identification and sharing of qualitative and quantitative information with potential recipient projects. Establishing what demand there is for components in advance of demolition led to reclamation of certain items, prevention of waste and, in some cases, displaced procurement of new materials.

Once adequate E-BAMB information is made available to potential recipients, it is easy for them to consider possibilities for direct reuse. Repurposing and upcycling, however, require a leap of imagination. Sections 4.2 and 5.2 both emphasised the role of creativity in inventing new, value-adding uses of materials. Quantitative information generated by pre-redevelopment

audits, and most in-use stocks research, does not lend itself to imaginative thinking. In the case study projects, a photographic inventory and a loose idea of quantities was an effective starting point in spurring ideas. Sometimes this was enough to establish usefulness and demand for components. On other occasions, further information was necessary before progress could be made in designing components into a scheme or committing to taking materials. When further information was needed, it was provided by more detailed survey, correspondence with both the supply and demand side, and sometimes by holding meetings. In these cases, the flow of information between supply and demand projects was initiated and had to be sustained by the researcher – a resource not normally available to housing organisations. Nor does the role of ‘E-BAMB information broker’ exist in the wider industry. For single housing organisations, like the industrial sponsors, a scaled-down version of the triage with minimal resourcing was described. In the city-scale deployment of the triage, three possible ways to address the gap present themselves.

Firstly, there is the optimistic view that creating an E-BAMB information system, as described in section 5.2, and introducing policies to incentivise its use, will in time create lines of communication between supply and demand projects to their mutual benefit. A database that collates and broadcasts audit information will depend on the quality of the audit, so unless this is very detailed in the first instance, it is likely that some potential recipients will require further information. People will still need to talk to establish the information pertinent to a particular demand project. If conversations are not fruitful and do not lead to material exchange, will a participant have the motivation to try again in future?

A second option is that the role undertaken by the researcher in the live case studies could be professionalised. This would be akin to the role of superuse scouts envisaged by van Hinte et al. (2007): a sector made up of individuals and companies with expertise in both the availability of and need for secondary components. Questions about such a business model arise: what price will supply and demand projects be willing to pay for a transaction that already appears financially dubious on both sides?

The third approach, then, is for the information brokerage role to be within the remit of intermediary enterprises that upcycle and repurpose materials. Or, to put it another way, the superuse scout may need to integrate some form of material handling for their service to add sufficient value. Such an intermediary will have information as well as material interfaces with both supply projects (as an alternative to a waste management company), and with demand projects (as an alternative supplier). The relationships are similar to current contractual arrangements; developers and contractors are relieved of the need to form unfamiliar connections from ‘grave-to-cradle’. Approximations of this model are Rotor Deconstruction in Brussels and Retrouvius in London; both reclaim, condition and sell materials, as well as providing consultation on reuse.⁹ Most of their products are simply prepared for reuse, though,

⁹ <https://rotordc.com/>; <https://www.retrouvius.com/home>

rather than attempting to take lower value materials and upcycle them. The next chapter considers an example of the kind of upcycling intermediary proposed in Chapters 4 and 5.

Leaving the discussion of the E-BAMB information system at this point is not to suggest that this area of research should be put to one side. As discussed in section 5.2, further investigation with a view to implementation alongside accompanying policy measures should be pursued in support of direct reuse, as well as to create a context of information on which ideas for intermediary businesses can be founded. However, the role of intermediaries appears to be critical, so the next part of the thesis shifts focus, from urban and information systems, to a single product and an enterprise system. It examines the viability of a notional enterprise and the material process it would carry out, and adopts the perspective of the enterprise to reflect on what would make its emergence, and the emergence of other similar enterprises, more likely.

6 ENGINEERING THE SYSTEM OF CROSS-LAMINATED SECONDARY TIMBER

6.1 Introduction to product and enterprise-level investigation

The previous two chapters contributed to the understanding of existing C&D waste management, and developed from this understanding an alternative future scenario of component management. They identified possible steps to reach this scenario, and explored means of addressing the significant gap in E-BAMB knowledge to create enabling conditions for reuse, repurposing and upcycling. To test the credibility of these theories and address the third research objective, Chapter 6 focuses on one material group and moves from the scale of urban systems to the scale of a particular product and the enterprise realisation system that would manufacture it.

Section 6.2 explains the rationale for a focus on timber, the existing context of waste wood removed from building stocks and the present use of CLT in new construction. As section 6.3, the chapter includes Rose et al. (2018), which tests the technical implications of using secondary timber to make CLT. Section 6.4 places the material intervention in the wider systems engineering model and examines the practical and economic feasibility of a CLST enterprise in relation to the triage activities established earlier. In doing so, it provides a lens through which to scrutinise the implications of the urban proposals; while, in itself, representing a pragmatic response to one material group and a potential future business opportunity.

6.2 Context: timber removed from existing building stock and CLT additions to stock

6.2.1 Narrowing the focus to timber

Much of the research into secondary use of specific construction materials focuses on the mineral fraction, which in most European economies represents the great majority of C&D waste generation. For reasons of quantity alone, this attention is warranted. However, it would be a mistake to allow focus on this fraction to overshadow smaller yet still vast quantities of other materials.

The choice of timber as an example material to explore in more depth may seem counterintuitive. Wood is one of the planet's renewable resources and is unique amongst major construction materials for renewing through conversion of solar energy into useable material within a timeframe that allows it to be used sustainably (Ramage et al., 2017a). It is commonplace in construction to specify certified timber that ensures that it is forested in a sustainable way. There is not thought to be any immediate concern about deforestation due to increasing use of timber in construction; in Europe, forest cover has increased by 6% since 1990, and growing demand can be met by more efficient management of existing forests, more efficient processing of timber and by extending current forested land (Ramage et al., 2017a).

However, in the long term, global use of biomass as a material (largely timber and paper) faces increasing competition with use of biomass as fuel and food – and total biomass production cannot rise significantly (Allwood et al., 2011). Timber is considered one of three major future resource risks facing the UK construction industry (along with aggregates and copper), primarily due to availability and rising prices associated with increased global demand (Defra, 2010).

There are practical reasons both for and against a focus on timber as a case study of upcycling. Timber is one of the commonest materials, widely used throughout history (an assessment of timber stocks is provided in Appendix B and an estimation of timber emerging from building stock is provided in Appendix S). It arises as a waste stream from the industrial sponsors' projects – so it has practical implications in the research setting – though in relatively small quantities compared to masonry and rubble. It is lightweight and easily handled in comparison to low value, high density rubble. Tools and equipment for reworking timber are commonly available; carpentry skills can often be found locally and are relatively easily developed, creating the potential for social benefits. Unlike metals, timber does not have scrap value when leaving a construction site, so contractors are predisposed to consider options that avoid gate fees; there is impetus to seek value-adding alternatives to waste management. Timber can age well aesthetically; on the other hand, it can deteriorate, particularly if exposed to weathering during its use in buildings. If the moisture content of timber exceeds about 20% dry mass, it becomes susceptible to attack by insects, bacteria and fungi (Sonderregger et al., 2015). C&D wood waste may have been subject to preservative treatments and it may contain contaminants such as paint and nails. These factors can make it harder to handle and reuse, and in some instances, it is considered hazardous. Different species of softwood and hardwood are used in construction, with differing properties; and alongside solid timber, typical wood waste from C&D may contain several other types of wood products. Therefore there is no single solution to the reuse of secondary timber. However, compared to, for instance, building services products like lighting, timber can be classified into relatively few generic groups. Unlike products that serve very specific functions and are made up of many parts, like a window, timber frequently emerges in C&D waste as a single material. These traits make it simpler for timber to be adapted to serve new purposes. Finally, as most wood waste is currently downcycled or incinerated (Defra, 2016; Tolvik, 2011), it is a material group that presents considerable potential for improvement in the use of its residual performance.

6.2.2 Existing context and the idea of cross-laminated secondary timber

The notion of using secondary timber in the production of CLT came from a period of reflection after carrying out the case study research described in Chapter 4. There was, and is, a growing interest in the ability of CLT to challenge the use of concrete or structural steel on a range of building projects (Jones et al., 2016). This can include education, housing, civic and commercial sectors (Crawford et al., 2015); CLT was used for the school buildings in a Poplar HARCA project (section 5.4.3) and is proposed for the new build elements of Fashioning Poplar

(section 5.4.4). The construction of ever taller timber buildings – nine storeys in London; then ten in Melbourne, fourteen in Bergen, eighteen in Vancouver; by 2019, 24 in Vienna (CTI, 2017; Foster et al., 2016) – and the prospect of building higher still, has caught the attention of mainstream media (Hunt, 2018; The Economist, 2016) as well as industry and academia (Chapman, 2012; Foster et al., 2016; Green, 2012; Ramage et al., 2017b; Wells, 2011; Yates et al., 2008). CLT's advantages over other structural materials include, in design, being relatively lightweight and thus requiring smaller foundations, improved air tightness and BIM integration; and on site, speed of construction, cleaner and quieter working environments, fewer site deliveries, and lesser construction waste generation (Jones et al., 2016; Kremer and Symmons, 2015). Forms of off-site manufacture such as CLT are increasingly seen as the way to make efficiency gains and 'modernise' the construction industry (Farmer, 2016; Gavron et al., 2017). The material cost of CLT is higher than concrete, but it can achieve savings in substructure and reduced contractor overheads based on shorter construction periods. In a detailed cost comparison of a CLT and a concrete design for a seven-storey residential building in London, these factors led to a net uplift of less than 0.2% for the CLT (Hyams et al., 2017).

Legal & General Homes developed the UK's first plant for assembly of CLT modular housing, and Swan Housing Association have followed suit, but the CLT is currently still imported from mainland Europe (Barker, 2017; Farmer, 2016; pers. comm. Liddell, 2017). It was recently announced that the Construction Scotland Innovation Centre¹⁰ is producing the first UK-made CLT – notwithstanding this author's own small-scale pilot (section 5.4.3) – for a pavilion to be installed at the Victoria & Albert Museum (Marshall, 2018). The CLT for the pavilion is made from hardwood: imported North America tulipwood (Construction Scotland Innovation Centre, 2018). Although researchers from Edinburgh Napier University have investigated the use of home-grown timber (Crawford et al., 2015; D. Crawford et al., 2014), this has yet to be implemented.

The idea of CLST originated from the researcher's immersion in the issue of C&D waste and the swell of attention received by CLT. Local reprocessing of secondary timber into a valuable product would appear to hold potential for environmental, economic and social gains, over both conventional production of CLT and current timber waste management. These are indicated in a schematic diagram of a proposed CLST life cycle (Figure 29), and discussed in section 6.2.3.

¹⁰ <http://www.cs-ic.org/>

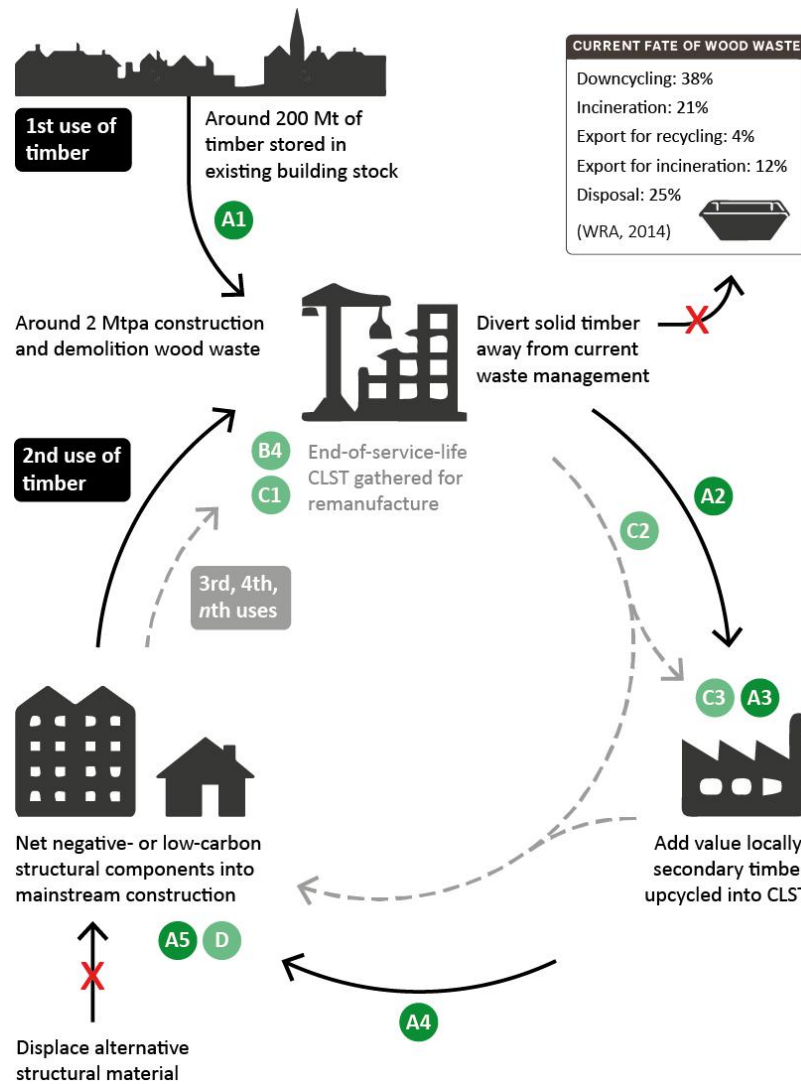


Figure 29: Life cycle schematic for cross-laminated secondary timber; life cycle stages as BS EN 15643 (BSI, 2012a) indicated in green. Dashed inner line represents potential multiple use cycles of CLST designed for deconstruction and reuse.

6.2.3 Sought context and the life cycle design of cross-laminated secondary timber

The sought context is one in which premature downcycling, incineration and disposal of reusable timber is avoided and the material is instead reused, repurposed, or diverted into feedstock for upcycling processes. CLST is an intervention that could help to bring that about. Table 22 provides a commentary on the potential relative merits of the introduction of CLST in comparison to two existing scenarios: (i) standard timber waste management plus use of concrete and steel for new construction; and (ii) standard timber waste management plus use of conventional CLT – henceforth to be termed cross-laminated primary timber (CLPT) – in new construction. A third scenario (iii) is considered in which CLST does not replace other materials in new construction but instead provides additional construction, i.e., there are no displacement benefits but greater material services are achieved. The discussion is structured around the life cycle stages from the family of standards BS EN 15643 (BSI, 2012a), as indicated in Figure 29. Use stages B2-B3 (maintenance, repair) and B5-B7 (refurbishment, operational energy use,

operational water use) are not discussed because they are assumed to be the same for CLST as for other materials.

Table 22: Commentary on potential life cycle environmental, social and economic performance of CLST

Life cycle stages as BS EN 15643	Potential environmental, social and economic comparison of CLST to other scenarios as described above; where no number is shown, no major differences exist
Raw material supply (A1)	<p>(i, ii, iii) Secondary timber diverted away from waste management – saving on transportation, processing; delay of energy generation until end of material use; delay release of sequestered carbon to atmosphere. More employment involved in preparing for reuse than in disposal (BioRegional and Salvo, 2010; Gorgolewski, 2008).</p> <p>(i) Extraction of resources and primary production of cement, sand and aggregate/steel avoided. A review of LCAs by Master’s collaborator showed that cradle-to-gate (A1-A3) assessments consistently find CLT to have lower impacts than concrete or steel (Zou, 2017).</p> <p>(ii) Approximately 90% of energy use in primary timber supply can be attributed to kiln drying (Ramage et al., 2017a) – avoided when reusing timber that has already been dried. In a US cradle-to-gate study of softwood framing (equivalent to raw material supply for CLT), ‘cumulative energy consumed in producing virgin compared to reclaimed framing lumber was about 11 times greater. Global Warming Potential was about 3 times greater,’ (Bergman et al., 2010).</p>
Transport of materials from extraction to manufacturing site (A2)	<p>(i, ii, iii) Distances are unknown, but collecting secondary timber will involve many trips to different urban sites; potentially this is no different to current waste management if sourced from WTS where timber is already consolidated.</p> <p>(i, ii) Distances from mine/forest to manufacturing sites are unknown, but transport can be arranged efficiently.</p>
Manufacturing (A3)	<p>(i, ii, iii) More industry and jobs close to cities, supported e.g., by Social Value Act (HM Government, 2012).</p> <p>(i) Avoided impacts of concrete or steel manufacturing; as noted above, LCAs consistently find CLT to have lower impacts than concrete or steel (Zou, 2017).</p> <p>(ii) CLST and CLPT manufacture assumed to be the same by (Zou, 2017), but unlikely in practice, as secondary timber is likely to be smaller pieces, requiring more jointing and lamination to reach the functional unit, and possibly also a larger section to achieve equivalent mechanical properties. Yield likely to be greater from secondary timber that is already sawn to one of a number of common thicknesses than from logs; but secondary timber may include sections with fixings and manmade defects that cannot be used. To address this there is likely to be additional equipment to detect metals and areas of low density and remove by cross-cutting.</p>
Transport from gate to site (A4)	<p>(i, ii) Reducing imported construction materials minimises transportation, contributes to the goal of 50% reduction in construction industry trade deficit (HM Government, 2013b) and benefits local economies.</p> <p>(ii) The majority of CLT used in the UK is imported from Austria (Crawford et al., 2015), and can be assumed to travel a distance of 1,500 km by road (Papakosta and Sturgis, 2017). This has a significant influence on the product’s life cycle impacts (Zou, 2017).</p>
Assembly (A5)	<p>(i) CLST and CLPT involve less site-based employment than concrete. Proposal to make smaller, modular panels that can be moved without a crane could reduce the speed of construction of CLST or CLPT, or could make it faster due to potential ability to have installation proceeding in more than one area at a time; or if much smaller so as to be handled manually, could replace energy needed for plant with labour.</p>
Use (B1)	<p>(iii) Using secondary timber to provide additional material services through CLST could, depending on the percentage harvested, deliver the structural materials for 3,700-10,000 new dwellings per annum, focusing only on the four regions with the highest waste generation, and assuming that 50% of the solid wood waste fraction is suitable and production yield is 60%. An account of the sources of data, assumptions and calculation process is provided in Appendix T.</p>

Life cycle stages as BS EN 15643	Potential environmental, social and economic comparison of CLST to other scenarios as described above; where no number is shown, no major differences exist
Replacement during building use (B4)	(i) Design could be developed to allow CLST or CLPT panels to be replaced and building adapted, potentially prolonging building life and making adaptation less costly than in concrete framed building.
Deconstruction and demolition (C1)	(i) Design could be developed to allow CLST or CLPT structures to be deconstructed, potentially with more manual labour than the large plant needed for concrete demolition.
Transport to waste processing (C2)	(i) Avoidance of export of steel for recycling.
Waste processing (C3)	(i) Avoidance of the energy needed for steel recycling, design could be developed to allow CLST or CLPT panels to be refurbished and upgraded, e.g., by planting on new facing layers.
Disposal (C4)	(i) CLPT and CLST ultimately release sequestered carbon back into the atmosphere. Avoiding toxic adhesives and treatments could allow nutrients in CLST or CLPT to return to biological cycle.
Benefits and loads beyond the system boundary: reuse, recovery or recycling potential of CLST (D)	<p>(i, ii, iii) Ability to displace future primary production in subsequent cycles; standard waste management ends timber's material life (incineration) or produces recycled products that have little or no ability to be recycled or reused.</p> <p>(i) End-of-life concrete recycled as aggregates entails loss of embodied such that only the relatively low embodied emissions of aggregate can be displaced.</p> <p>(ii) CLST or CLPT could be designed to seek improvements on the likely end-of-life scenario of current CLT. This could include innovation in fixings, material passports and RFIDs; BIM integration for information management; modular panel design; panel sizes that can be handled in standard workshops that can be found in and around cities.</p>

The commentary in Table 22 is a preliminary assessment of the implicit or expected effects of introducing a system of CLST. In an attempt to quantify the environmental differences between CLST and CLPT, an LCA comparison was carried out by a collaborating Master's student (Zou, 2017; Appendices I-6 and U). This study found that in cradle-to-gate (A1-A3) assessment, CLST had lower impacts in some categories, including a global warming potential 6% lower, and CLPT had lower impacts in others. In cradle-to-site (A1-A4) assessment, CLST impacts appear to be considerably lower in many categories, including a global warming potential 80% lower. The cradle-to-site assessment showed that if CLST production is assumed to be a distance of 50 km from the source of secondary timber and from the construction site where it is used (e.g., in the hinterland of London or located so as to be able to serve several major northern cities), then the small transportation impacts, in comparison to CLPT imported from Austria, are the decisive factor in many impact categories. The use of chemical treatments to remove paint and other contaminants from secondary feedstock led to higher impacts in ecotoxicity potential categories and human toxicity potential; using non-toxic agents or removing surface treatments mechanically can significantly reduce the impacts of CLST. At this preliminary stage in the development of CLST, it would be inappropriate to give great credence to other observations that could be drawn from this LCA, as it is based on many assumptions. From the perspective of 'impact reduction potential' (section 2.5.3), the rate of actual displacement of other primary production is critical; at present, CLPT appears to have the credibility to displace concrete or steel in many instances, while it will take considerable time to demonstrate that the same is true of CLST. The LCA suggests that CLST would bring

environmental gains if it can be implemented. However, at this stage, the findings of a detailed LCA are of less relevance than the question of CLST's practicality and ability to perform a structural purpose. The next section begins the process of addressing this question.

6.3 Cross-laminated secondary timber: towards a proof of concept¹¹

6.3.1 Introduction and review of secondary timber properties

The timber in existing building stocks represents a significant stockpile, with estimates in the range of 2.4-4.0 tonnes per capita (Höglmeier et al., 2013; Kleemann et al., 2017); in some countries, it is a greater quantity than the stock in forests managed for harvesting (Müller, 2006). Upon building demolition, the cascading principles that form the basis of a circular economy (Ellen MacArthur Foundation, 2013; Stahel, 1982) dictate that the resulting timber arisings should be reused (Bergman et al., 2013, 2010; BioRegional, 2006), with minimised processing and loss of performance, to maximise their useful lifespan (Fraanje, 1997; Sirkin and ten Houten, 1994) and maintain storage of sequestered carbon (Husgafvel et al., 2017). The greatest opportunities for long-term use in the built environment lie in structural applications as they have the longest lifespan (Brand, 1994).

However, direct reuse of timber is often impractical, for reasons including the fact that buildings are rarely designed with deconstruction and reclamation in mind (Durmišević, 2015; Sassi, 2004). Conventional recycling involves chipping timber and downcycling it into products such as particleboard and animal bedding, which achieves reliable supply and fitness for purpose, but with a considerable loss of performance and value; the recycled products are relatively short-lived and represent the final material use before incineration or disposal. Any reclaimed whole members that reach the salvage yard tend towards shorter usable lengths and smaller effective sections. They may retain their mechanical characteristics (Falk et al., 2008), but are typically sold 'as seen' and without warranties, failing to provide certainty over supply and fitness for purpose, which restricts demand from mainstream construction (Rose and Stegemann, 2018a).

Improving the supply of secondary timber to the construction industry could mitigate future risks, including increased competition for the use of land (Allwood et al., 2011), price rises if timber supply is curtailed while demand rises (Defra, 2010), and future planning requirements, contractual obligations and regulation of whole life greenhouse gas (GHG) emissions (BIS, 2010; Giesekam et al., 2015, 2014; Papakosta and Sturgis, 2017; Steele et al., 2015). However, to capitalise on residual timber performance, there is a need for new processes that upcycle secondary timber, and recertify the resulting products to meet mainstream construction industry requirements (Rose and Stegemann, 2018a, 2018b).

¹¹ Portions of the text that describe work that was undertaken primarily by a collaborator from a different discipline are reproduced in italics. See section 1.3.3 for a statement of the present author's contribution to the paper.

This research proposed to exploit secondary timber as a feedstock for cross-laminated timber (CLT). The use of CLT has grown considerably in recent years; its advantages are well understood in academia, and it is gaining acceptance across industry (Jones et al., 2016). Production capacity is rising, with Austria and Germany reporting 20% year on year increases (Hairstans, 2016) and double-digit annual growth rates expected over the next decade (Brandner et al., 2016). The manufacture of CLT panels from variable feedstock in crosswise laminations minimises the detrimental influence of natural defects in individual boards of primary timber (Concu et al., 2017; Taylor, 2013), and the same effect could be expected with defects arising from previous use of secondary timber. Laminated timber products also provide an opportunity to control the location of higher grade timber in the engineered section to maximise structural benefit. Glulam standard BS EN 14080:2013 (BSI, 2014a) already endorses production of structurally efficient sections from variable quality wood, with stiffer and stronger timber at the extremities of the section, and weaker timber at the neutral axis, the function of the latter being primarily to increase the second moment of inertia by separating the outer lamellae. Based on Mechanically Jointed Beams Theory (MJBT, also known as the Gamma Method; Eurocode 5; BSI, 2014b; Christovasilis et al., 2016), a similar approach can be seen for CLT products, for which typical current European practice for strength and stiffness calculations largely disregards the contributions of the lamellae crosswise to the load application, e.g., horizontally-oriented lamellae in a vertical compression element (wall), or lamellae oriented orthogonally to the span in a bending element (floor) (Milner, 2017).

Mining cities' existing timber stocks could enable greater self-sufficiency of cities in managing their construction and demolition waste (e.g., GLA, 2017) and help to localise CLT supply chains (Brunner, 2011). For example, as the UK has little forest cover (12% of total land area, compared to 47% in Austria; FAO, 2011), CLT, in particular, is imported to the UK from Austria and other parts of Europe. On the other hand, the timber fraction of UK construction and demolition waste is estimated at 0.9-5.0 Mtpa (Defra, 2012c; Pöyry, 2009; Tolvik, 2011; WRAP, 2011), of which something in the region of 55-75% is solid wood (Pöyry, 2009; WRAP, 2011), and a growing proportion of this waste is exported for energy generation in Europe (Defra, 2016; Tolvik, 2011; WRAP, 2011). Using secondary timber stocks would contribute to policy goals: fostering a more circular economy with new employment in manufacturing (Gavron et al., 2017) and reindustrialisation of the European (and British) economy (European Commission, 2015, 2014, 2012), and production of net negative- or low-carbon building components. The lifespan at high value of timber in a circular economy could be further extended by designing the cross-laminated secondary timber (CLST) panels for deconstruction and reuse (Campbell, 2018). If CLST can replace conventional CLT, structural steel and reinforced concrete in some applications, this is enhancement of the performance of waste: upcycling into a new closed loop.

Timber for different structural uses is graded based on its tree species, origin, strength reducing characteristics and geometrical characteristics (BSI, 2017, 2016a, 2016b, 2013). CLT is

typically made from Norway spruce and common strength classes are C24, C18 and C16 (Brandner, 2013). However, there is growing interest in and research on use of locally abundant, under-utilised timber resources for which there are no established structural properties as feedstocks for CLT (Espinoza and Buehlmann, 2018). Examples include the use of Sitka spruce in Scotland (Crawford et al., 2015; D. Crawford et al., 2014) and Ireland (Sikora et al., 2016); Italian marine pine in Sardinia (Concu et al., 2017; Fragiocomo et al., 2015); European beech in Germany and Switzerland (Aicher et al., 2016a, 2016b; Franke, 2016); large-leaf beech (Essoua Essoua and Blanchet, 2017), Southern pine (Hindman and Bouldin, 2015; Sharifnia and Hindman, 2017), hybrid poplar (Kramer et al., 2014) and tulipwood (Mohamadzadeh and Hindman, 2015; Thomas and Buehlmann, 2017) in North America; poplar (Wang et al., 2014) and eucalyptus (Liao et al., 2017) in China; and Japanese cedar (Okabe et al., 2014). Investment in a new CLT and glulam plant in Alabama that exploits local Southern pine (Vloysky, 2017) suggests that alternative feedstocks to those used in typical European CLT production can become economically viable if abundant local materials are used.

Although European Standard BS EN 16351:2015 (BSI, 2015) does not allow used wood in CLT as a precaution, it has also previously been suggested that secondary timber could be used to produce engineered wood products (Bergsagel, 2016; Geldermans, 2009; Kremer and Symmons, 2015; Sakaguchi, 2014). Researchers at the University of Utah with industry partners investigated the manufacture of interlocking 'ICLT' without adhesives or fasteners (Smith, 2011). Their work considered sourcing the timber from existing buildings, but they chose instead to explore pilot manufacture and mechanical testing of ICLT using standing trees that have been affected by pine bark beetle (Wilson, 2012). Thus, the concept of CLST has not yet been tested (notes on the novelty of CLST are included in Appendix V).

For certifiable mass production of CLT, consistency of supply of raw materials and raw material quality is crucial. As a natural material, the properties of primary timber may vary, and BS EN 16351:2015 (BSI, 2015) makes allowance for this by permitting deviation of up to 35% from the declared strength parallel to the grain in 10% of boards in any given lamella. Nevertheless, to achieve equivalent levels of confidence in secondary timber requires an understanding of how ageing and use affect both its characteristics and the variability of these characteristics.

Natural ageing results from biological, chemical, mechanical, thermal, water and other weathering effects (Nilsson and Rowell, 2012). When 'stored' in use in a building's structure, timber is typically protected from weathering, and moisture content should be below 20%, such that it is largely protected from biological degradation. Softwoods, which make up the majority of secondary timber, may benefit from increasing cellulose crystallisation for the first few hundred years of life (Kohara and Okamoto, 1955; Nakao et al., 1989), leading to increases in density, hardness, dimensional stability, tensile strength, and Young's modulus (the ratio of elastic stress and corresponding strain, also known as the Modulus of Elasticity, MOE; Lionetto et al., 2012). However, two recent review papers (Cavalli et al., 2016; Kránitz et al., 2016) found that there has been no overall consensus on the effect of natural ageing on strength,

stiffness and other physical properties of various species of timber. Ageing during use inside a building, e.g., through fluctuations in temperature, humidity or the effects of ultraviolet radiation, may affect timber's mechanical properties, but findings are often ambiguous, and could result from other factors (Attar-Hassan, 1976; Froidevaux and Navi, 2013; Holzer et al., 1989; Kránitz et al., 2016; Sonderegger et al., 2015). Surface characteristics of timber change with time (Kránitz et al., 2016) and, for use in CLT, the faces of secondary boards would need to be planed to provide a good surface for durable bonding as well as to produce consistent thicknesses.

It is well established that timber can carry substantially greater loads over a short period of time than for long durations of loading; Fridley et al. (1995) present a history of research investigating this 'duration of load' (DOL) effect going back to the eighteenth century. Much of the research into creep-rupture, the failure mode attributed to the DOL effect, uses results of impact testing and short- and long-term loading to estimate expected times until failure for loading at a given stress ratio (i.e., a proportion of assumed short-term strength; Hoffmeyer, 2003). Higher moisture content is known to produce a shorter time to failure, while cyclical changes in moisture content further accelerate creep and reduce time to creep-failure (Hoffmeyer and Sørensen, 2007). Since at least the nineteenth century, it has been understood that timber structures intended for long life should be designed with a safety factor such that only one-half to two-thirds of the material's short-term strength is relied upon (Fridley et al., 1995). The effects of DOL and moisture content have long been incorporated into design standards for timber building structures; e.g., Eurocode 5 (BSI, 2014b) sets out strength modification factors ranging from 0.50 for 'permanent' loading (>10 years) in climatic conditions that may lead to moisture content >20%; 0.60 for permanent loading where moisture content is <20%; to 1.10 for instantaneous loading for moisture content <20%.

It is important to note that DOL effects are particularly significant in the short- and medium-terms. In the long-term, a difference of double or triple the anticipated load duration affects the load capacity by only a few percentage points (Hoffmeyer, 2003). The major reduction in load capacity predicted by DOL modelling occurs over the first few years – and certainly within a period of time in the order of a normal building lifespan of, say, 50 years – with further degradation beyond that time found to be minimal in most DOL research (Dinwoodie, 1975; Hoffmeyer, 2003; Wood, 1960). This seems to bear out the observation that many very old timber structures remain standing. Arguably, therefore, secondary use of timber simply extends its anticipated load duration and could be expected to produce only minor reduction in load capacity, compared to the strength modification factors taken into account in its first use.

Nevertheless, uncertainties remain. Timber that has been exposed to high and especially to fluctuating moisture content, for instance through external use, is likely to have experienced significant strength loss and is unlikely to be suitable for reuse in a structural application. Evidence suggests that large solid timber members used internally do not undergo large moisture fluctuations (Holzer et al., 1989), but this may not always hold true. Repeated loading

may have caused fatigue damage to have accumulated in secondary timber that cannot be perceived (Hoffmeyer, 2003). The stress ratio at which loss of strength becomes permanent appears to vary widely depending on timber species and testing conditions, with an average perhaps in the region of 0.40 (Dinwoodie, 1975). On the other hand, different conclusions arise from the extensive work by the USDA Forest Products Laboratory on the structural properties and grading of North American secondary timber (Falk, 2002, 1999, Falk et al., 2012, 2008, 2003, 2000, 1999b, 1999a, 1990; Falk and Green, 1999; Fridley et al., 1996; Janowiak et al., 2014; Williams et al., 2000). They acknowledge that 'overloading' can degrade timber, but their testing indicates that MOE and bending strength appear to be unaffected by ageing and previous load history (Falk et al., 2008), and that reductions in strength arise from observable macro-level defects, such as nail holes, rather than from the molecular structure of aged timber. They therefore recommend regrading before reuse but conclude that wholesale visual downgrading is currently too conservative. The group consider some reuse options for different species of reclaimed timber (Janowiak et al., 2007, 2005), including nail-laminated posts (Janowiak et al., 2014). They were able to conclude that the tested material has potential for reuse in this structural application, but have not extended their investigation into CLT.

On this basis, preliminary research to explore the technical feasibility of using secondary timber to produce CLST was conducted. The specific objectives were:

1. To make CLST and cross-laminated primary timber (CLPT) at small-scale;
2. To examine and compare the compressive and bending strengths of the CLST and CLPT prepared in (1) using standard laboratory tests;
3. To examine the potential effects of manmade defects on properties of CLST using finite element modelling (FEM);
4. To examine the potential effects of reduced properties of individual lamellae (potentially arising from ageing, history of loading and climatic conditions), on the effective overall section properties of CLST using MJBT;
5. To make recommendations for further research necessary to advance this concept to pilot-scale and commercial application.

Laboratory testing, FEM and MJBT were undertaken as complementary techniques to examine the potential effects of previous use of secondary timber feedstock on CLST, whereby the modelling techniques enabled additional preliminary investigations without the need for further physical testing. FEM was used to model specific defects, whereas MJBT is a relatively simple calculation that allowed the possible overall effect of feedstock ageing to be examined without undertaking extensive FEM.

Timber

Mixed-species softwood boards collected by a reuse enterprise (Remakery Brixton Ltd, 2018) from construction and demolition sites across London over a period of 2-3 years, were surveyed for defects (Table 23) and used to make CLST in the UCL laboratory. This secondary timber had been stored horizontally indoors at ~65% relative humidity and had a moisture content of $13.7 \pm 0.8\%$ dry mass, based on testing in triplicate according to BS EN 13183-1:2002 (BSI, 2007). Board lengths used for CLST ranged from 300-900 mm; board cross-sections varied from 90-170 mm in width and 20-45 mm in thickness.

The survey of 30 boards with a total length of 43.8 m considered manmade holes that would be considered natural knots and ‘abnormal defects’ in BS 4978:2007 (BSI, 2017). With reference to visual grading rules for softwood (BS 4978:2007; BSI, 2017), defects were grouped according to their cause and the natural defects that they resemble (Figure 30), for use in the FEM. Manmade holes had been formed by nails, screws and bolts (counted regardless of whether the fixing was still present), and two members had jointing notches. BS 4978:2007 (BSI, 2017) allows abnormal defects if their effect is ‘obviously less than that caused by the defects admitted by the grade’. A further four members were rejected because excessive distortion meant that they could not be worked with the machinery available. No members exhibiting wet rot were found.

Table 23. Survey of defects in secondary timber – categories and findings.

Defect	Description	Similar natural defect and reference	Number per linear metre
Small nail holes	< 2 mm diameter, not all the way through member	Worm hole/pin hole; allowed in (BSI, 2017)	6.8
Large nail holes	2-4 mm diameter, not all the way through member	Small knot hole; allowed in (BSI, 2015)	3.0
Screw holes	< 6 mm diameter, not all the way through member	Small knot hole; allowed in (BSI, 2015)	0.8
Through screw holes	< 6 mm diameter, all the way through member	Small knot hole; allowed in (BSI, 2015)	0.6
Bolt holes	6-10 mm diameter, all the way through member	Large knot hole; (BSI, 2017)	0.5
Notches	Rectangular cut-outs nominally 20x40 mm	Excessively large knot hole; rejected in (BSI, 2017)	0.0
Small knots	Disregarded if < 6 mm	(BSI, 2015)	n/a
Large knots	> 6 mm diameter	(BSI, 2017, 2015)	2.8

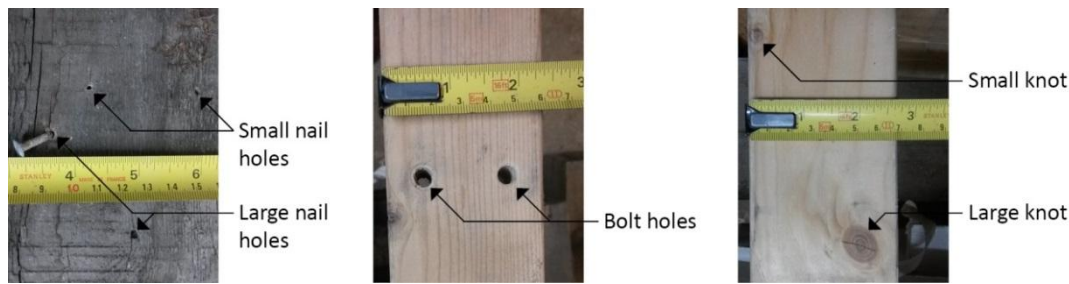


Figure 30. Timber defect survey – nail holes, bolt holes and knots.

To be able to observe differences between CLST and CLPT, and avoid confounding these with production quality differences arising from the use of laboratory woodworking equipment versus commercial CLT factory equipment, CLPT was also made in the UCL laboratory, with new kiln-dried Scandinavian pine from a timber merchant (Travis Perkins Redwood Planed Timber). The moisture content of the purchased timber was measured to be $12.5 \pm 0.8\%$ dry mass. The 2400 mm boards had a cross-section of 94x20 mm.

Preparation of cross-laminated secondary and primary timber

Both the secondary and primary timber boards were trimmed to a uniform cross-section of 80x17 mm. As equipment for machine grading or a trained visual grader were not available, all timber was informally graded based on the presence and size of knots, distortion of members, and slope of grain, with reference to BS 4978:2007 (BSI, 2017). Rounded or chamfered arrises (edges of members) and wane (naturally rounded edges of members arising from the milling of logs) were removed in the trimming process. In each case, the best grade was reserved for use in the outer lamellae.

Preparation of the CLST and CLPT mirrored the commercial CLT fabrication process (e.g., Stora Enso, 2014) as closely as possible. A commercial single-component polyurethane (PUR) adhesive manufactured by Kingfisher was used to glue the timber into lengths, lamellae and panels. Boards were finger-jointed flatwise using a CNC machine with a cutter bit parallel to the grain (Figure 31a), which were then glued and clamped. After curing for 24 hours, boards were cut to length and bonded edge-to-edge (again using customised clamps) to form lamellae (Figure 31b). The cured lamellae were then layered with adhesive in a customised mould, with each lamella perpendicular to the next. The adhesive spread rate was around 105 g/m^2 . A hydraulic press (Figure 31c) was used to apply a uniform compressive stress of 0.05 MPa, which is considered appropriate for PUR (Brandner, 2013). Due to the limitations of the press, the panels had overall dimensions of 820x320 mm; one 5-lamella (85 mm thick) panel (Figure 31d), for use in compression testing, and one 3-lamella (51 mm thick), for use in bending tests, were produced and cut to produce test specimens.

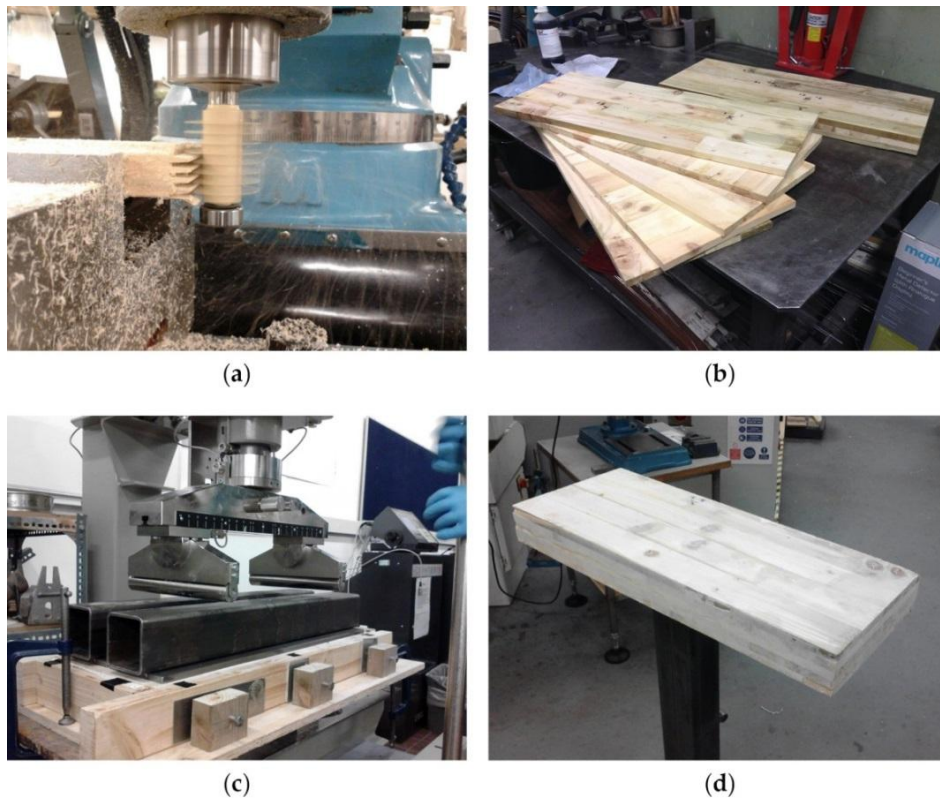


Figure 31. Cross-laminated secondary timber (CLST) production in the laboratory: (a) finger-jointing; (b) lamellae from secondary timber; (c) hydraulic pressing of lamellae; (d) 5-lamella CLST specimen.

Laboratory testing of cross-laminated secondary and primary timber in compression and bending

Unconfined compressive strength (UCS) was measured in triplicate based on BS EN 408:2010 (BSI, 2012b), using an Advantest 9 control console fitted with a compression frame of capacity up to 2000 kN. 85x85x85 mm specimens were uniformly loaded on all three axes (Figure 32). Deflection was monitored using a linear variable displacement transducer (LVDT) with maximum travel distance of 50 mm. The load was applied at a steady rate of 4.25×10^{-3} mm/s in the X and Y directions, and 0.425 mm/s in the Z direction, until measurement of the UCS at failure (BS EN 408:2010; BSI, 2012).

CLT specimens were subjected to destructive four-point bending tests in accordance with BS EN 408:2010 (BSI, 2012b), again in triplicate. To maintain the specified span-to-depth (L/d) ratio of 15:1 despite limitations on specimen length produced in the UCL laboratory, specimen depth and width were set to 51 mm for a span of 765 mm. An Advantest 9 control console fitted with a flexural frame with loading capacity up to 500kN was used. The two loading heads were located at the third points (i.e., a distance of 255 mm from each end support). The specimens were loaded symmetrically parallel to the grain direction of the outermost lamellae, i.e., out-of-plane bending of the panel's X-axis around the Y-axis in Figure 32, at a loading rate of 25.5 $\mu\text{m/s}$, until measurement of the bending strength (modulus of rupture, MOR) at failure. The deflections were measured using an LVDT positioned centrally under the loading head and the corresponding loads were used to calculate the Local MOE in bending.

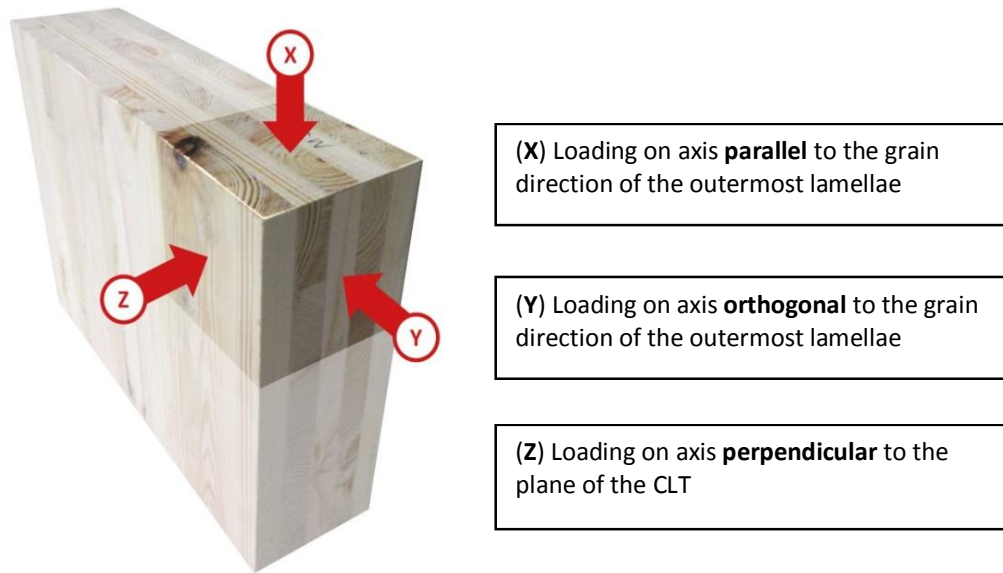


Figure 32. Different loading axes for compression testing (labelling according to BS EN 16351:2015).

Finite element modelling of effects of defects on cross-laminated secondary timber modulus of elasticity

FEM was used to estimate and compare the mechanical properties of CLST containing various timber defects. CLST behaviour in compression and bending tests to BS EN 408:2010 (BSI, 2012b) was simulated using ABAQUS to determine the MOE of CLST components with and without defects. Cubic elements (hexahedral C3D8R) with orthotropic material properties were used. The mesh contained four to five elements through the smaller thickness which was deemed sufficient for convergence.

Timber structures are designed elastically because the material fails in a brittle manner (Arya, 2009). Therefore, only the elastic behaviour of CLST was modelled, in keeping with other methodologies for modelling wood as a linear orthotropic material using ABAQUS (Carlberg and Toyib, 2012) and COMSOL (Baño et al., 2016). The timber properties were arbitrarily based on the elastic properties of Norway spruce at 12% dry mass moisture content (Domone and Illston, 2010).

To model the adhesive component, a ‘cohesive behaviour’ was added as a contact property between each of the lamellae. The normal and tangential elastic parameters of the adhesive, k_n and k_t , were obtained using the following equations and adhesive properties from the literature (Baño et al., 2016; Stoeckel et al., 2013):

$$k_n = \frac{E_{ad}(1-\nu_{ad})}{t_{ad}(1+\nu_{ad})(1-2\nu_{ad})} \quad (1)$$

$$k_t = \frac{G_{ad}}{t_{ad}} \quad (2)$$

where,

Poisson's ratio, $\nu_{ad} = 0.37$

MOE, $E_{ad} = 4 \text{ GPa}$

Shear modulus, $G_{ad} = 1.54 \text{ GPa}$

Bond line thickness, $t_{ad} = 0.5 \text{ mm}$.

To model their effects on the MOE of a CLST element, defects were introduced in the FEM at their maximum sizes in the defect survey (Table 23), with configurations as shown in Table 24 (Columns 2-5). Defects were placed such that those on neighbouring lamellae would not coincide, except for Run J, and the random defect positioning in Runs G, H and I. The notch (Runs I and J) was modelled to examine the effect of replacing three randomly placed small defects in each lamella with a single large defect of the same volume in each lamella. Hexahedral meshing was used to model different geometries of the defects, i.e., cylindrical knots, nail, screw and bolt holes, rectangular notches. The 'composite layup' module of ABAQUS allowed the grain direction of knots to be altered relative to the board grain direction (Runs L and N).

Table 24. Configuration of CLST with manmade (runs A-J) and natural (runs K-N) defects in 85 mm cubes with five lamellae for finite element modelling of compression tests.

Run	Defect type	Defect diameter x depth	Distance from sides of specimen (mm)	No. of defects per lamella	Resulting normalised MOE of CLST in compression on Y-axis (MPa)
A	None	n/a	n/a	0	1.00
B	Small nail hole	2 x 10	60 x 20 ^a	1	0.99
C	Large nail hole	4 x 10	60 x 20 ^a	1	0.99
D	Screw hole	6 x 10	60 x 20 ^a	1	0.98
E	Through screw hole	6 x 17 ^b	30 x 30 ^a	1	0.97
F	Bolt hole	10 x 17 ^b	30 x 30 ^a	1	0.96
G	Mixed	2 x 10, 4 x 10, 6 x 10	Random	3	0.96
H	Bolt hole	10 x 17 ^b	Random	10	0.84
I	Notch	20 x 40 x 17 ^b	Random	1	0.81
J	Notch	20 x 40 x 17 ^b	60 x 40 (all same spot)	1	0.79
K	Small knot at 90° to grain	12 x 17 ^b	60 x 20 ^a	1	0.94
L	Small knot at 45° to grain	12 x 17 ^b	60 x 20 ^a	1	0.96
M	Large knot at 90° to grain	24 x 17 ^b	60 x 20 ^a	1	0.87
N	Large knot at 45° to grain	24 x 17 ^b	60 x 20 ^a	1	0.87

^a Defect locations were rotated 90° for each lamella to avoid their coincidence; see Appendix W.

^b 17 mm is the full depth of a lamella.

Out-of-plane bending of the panel's X-axis around the Y-axis was modelled for a panel of the same dimensions as the laboratory bending test (Table 25). Initially, a single large hole was modelled at the centre of the span, and then shifted off-centre. Defects of the size and number identified in the survey were then introduced into each board at random locations along their length based on the typical dimensions and spacing observed in the survey. Finally, defects were concentrated at the centre of the span.

Table 25. Configuration of CLST with defects in 51x51x820 mm 3-lamella specimens for finite element modelling of bending tests.

Run	Description ^a	Resulting normalised MOE of CLST in bending (MPa)
P	No defect	1.00
Q	Single large hole located at centre of span	0.97
R	Single large hole located off-centre of span	0.98
S	Miscellaneous spread out holes	0.99
T	Miscellaneous holes clustered at centre of span	0.98

^a See Appendix W for further details of model geometry and positions of defects.

Mechanically Jointed Beams Theory analysis of effects of lamella properties on CLST stiffness

Use of FEM to examine defects was complemented by MJBT to examine the influence of reduced feedstock properties, which the existing literature suggests could come about from the effects of timber ageing, environmental conditions and the DOL effect. MJBT is widely used to calculate the overall bending stiffness of a built-up timber element, like a timber I-joist, by considering the independent bending stiffness of its constituent components (BSI, 2014b; Christovasilis et al., 2016). This is achieved by applying reductions in connection stiffness between the components to model the effects of fasteners, such as nails or glue, on the stiffness of the overall section.

To calculate the overall bending stiffness of a CLT element instead of a built-up timber element, the crosswise lamellae can be treated as fasteners with reduced stiffness, without separate representation of the adhesive. A CLT element was thus considered as a set of independent longitudinal lamellae (in the X-axis) fixed to the other lamellae in the section by fasteners with stiffness γ , a function of the rolling shear stiffness of the intermediate crosswise lamellae (Christovasilis et al., 2016):

$$\gamma = \frac{1}{1 + \frac{\pi^2 E_{0,x} t_x t_y}{L_{ref}^2 G_{r,y}}} \quad (3)$$

$E_{0,x}$ = MOE of the longitudinal lamellae

t_x = thickness of outer longitudinal lamella

$G_{r,y}$ = rolling shear modulus for the intermediate crosswise lamella

$$= E_{0,y}/160 \text{ (BSI, 2014b)}$$

t_y = thickness of intermediate crosswise lamella

L_{ref} = effective length of test sample (equal to test sample length for a pinned compression element, or simply supported bending element)

MJBT was used to calculate a CLT element bending stiffness $(EI)_{CLT,eff}$ in out-of-plane bending of its X-axis (i.e., around the Y-axis), which is a function of the MOE and thickness of the longitudinal lamellae, but also the MOE and thickness of the crosswise lamellae, and the length of the CLT element being considered:

$$(EI)_{CLT,eff} = \sum_{\substack{i=1 \\ i \text{ odd}}}^n (E_{0,i}I_i + \gamma_i E_{0,i} b t_i y_i^2) ; n = 3 \text{ or } 5 \quad (4)$$

I_i = second moment of area of each lamella, $n = b t_i^3/12$

b = width of overall section

y_i = distance of centre of lamella from overall section neutral axis

MJBT was also used to calculate the CLT element compression stiffness $E_{CLT,x} k_c$ with loading in the X-axis:

$$E_{CLT,x} k_c = \frac{\sum_{1 \leq i \leq n, i \text{ odd}} (E_{0,x,i} b t_i)}{\sum_{i=1}^n (b t_i)} k_c ; n = 3 \text{ or } 5 \quad (5)$$

where k_c is a factor to account for buckling effects using an I_{eff} derived from $(EI)_{CLT,eff}/E$ (BSI, 2014b).

As expected, the CLT compression stiffness and bending stiffness are both linear in relation to lamella stiffness, if the stiffness of all lamellae is altered equally. However, the k_c and I_{eff} components are non-linear functions related to the length of the CLT element, and the thickness of the crosswise lamellae.

To examine the effect of lamellae with reduced MOE on overall CLT compression stiffness and bending stiffness, the variables in Equations 4 and 5 were varied as indicated in Table 26. The overall section thickness was the same for all runs, whether the CLT had 3 or 5 lamellae. For Runs labelled “C”, the MOE of only the crosswise lamellae was reduced, using a range of values from 100% MOE (11000 MPa, based on C24) to 70% MOE (7700 MPa); for Runs labelled “L+C”, the MOEs of the longitudinal as well as crosswise lamellae were reduced in tandem, from 100% MOE to 70% MOE.

Table 26. Configurations of Cross-Laminated Timber for Mechanically Jointed Beams Theory calculations (overall section width, $b = 85$ mm and depth $d = 85$ mm).

Run	Span-to-depth (L/d) ratio	No. of lamellae of equal thickness	Lamella thickness, t (mm)	Lamella MOE (MPa)		Element length, L (mm)
				$E_{0,x}$	$E_{0,y}$	
10/3/C	10	3	28	11000	11000-7700	850
10/3/L+C	10	3	28	11000-7700	11000-7700	850
10/5/C	10	5	17	11000	11000-7700	850
10/5/L+C	10	5	17	11000-7700	11000-7700	850
30/3/C	30	3	28	11000	11000-7700	2550
30/3/L+C	30	3	28	11000-7700	11000-7700	2550
30/5/C	30	5	17	11000	11000-7700	2550
30/5/L+C	30	5	17	11000-7700	11000-7700	2550

6.3.3 Results of experiments and modelling investigations

Laboratory testing of cross-laminated secondary and primary timber in compression and bending

The ranked results from the compression and bending experiments of the CLST have been plotted against those for the CLPT in Figure 33. It appears that the properties of both materials were similar in compression, but that the bending strength of the CLST was about only 60% of that of the CLPT, whereas the MOE in bending of the CLST was about double that of the CLPT.

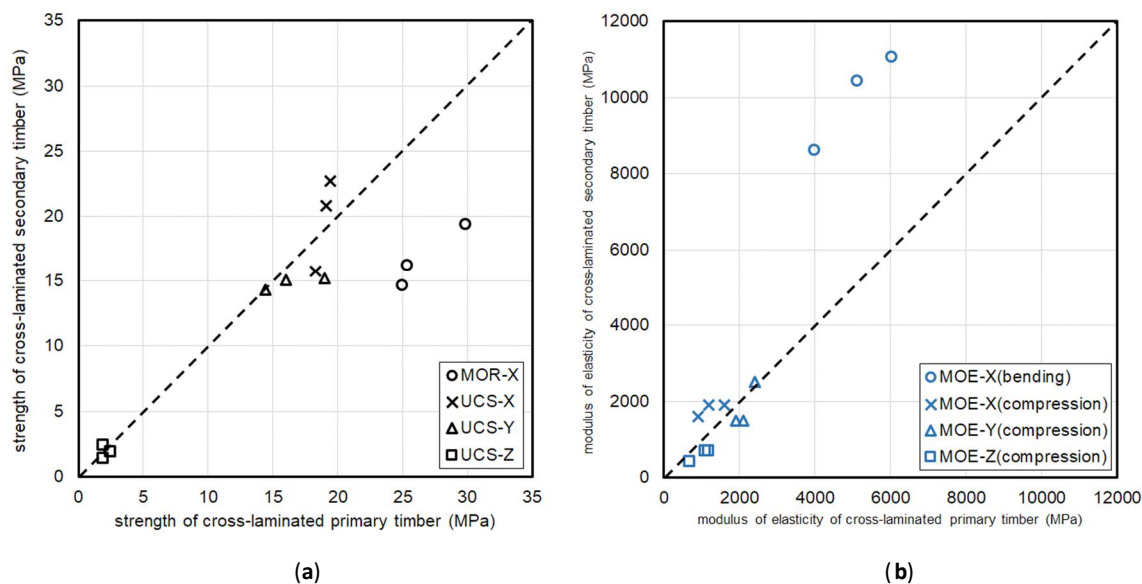


Figure 33. (a) Modulus of rupture (MOR), unconfined compressive strength (UCS) and (b) Modulus of Elasticity measurements for cross-laminated primary and secondary timber prepared in the laboratory.

There was some failure of adhesion between lamellae in both tests. Figure 34 shows that shearing and delamination occurred under compressive loading in both the X and Y directions, whereas densification occurred in the Z direction (in which CLT in use is not ordinarily loaded). In bending, failure largely resulted from tensile failure at finger joints (70% across all specimens) and knots (Figure 35).

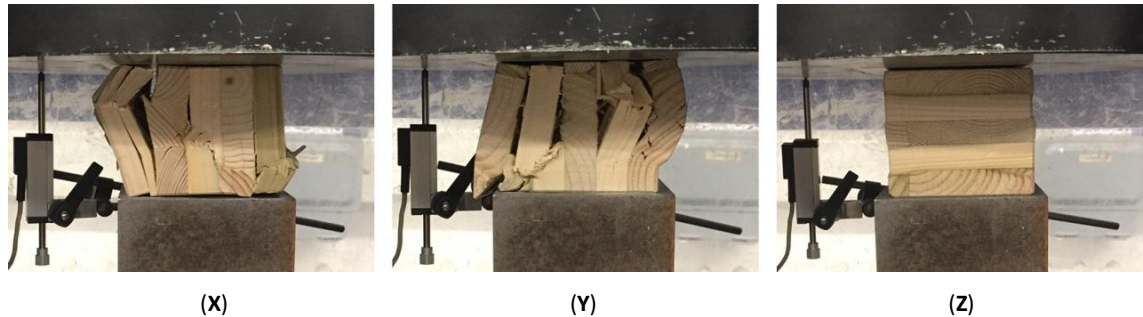


Figure 34. Specimens resulting from compressive loading on the three axes.

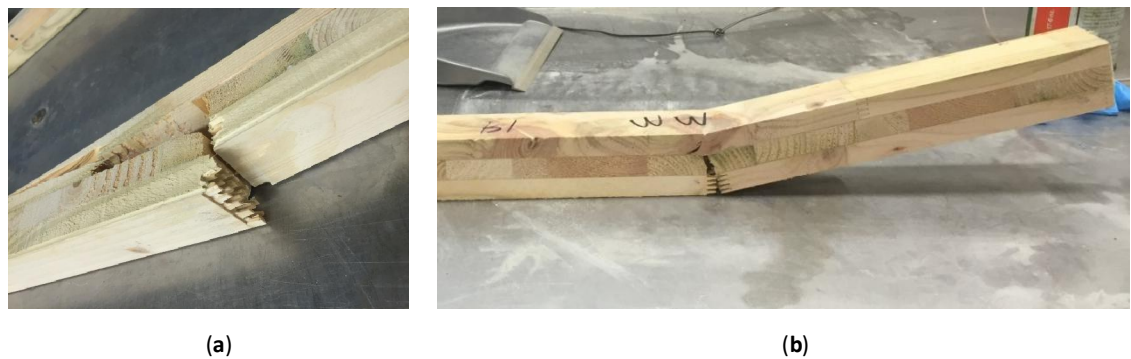


Figure 35. Bending failure (a) at finger joint and (b) at coincident finger joint and knot

Finite element modelling of effects of defects on cross-laminated secondary timber modulus of elasticity

MOEs estimated by FEM of specimens with defects are shown in column 6 of Table 24. As arbitrary timber properties were used for FEM in the absence of known values for secondary timber, the results in column 6 of Table 24 are expressed as reductions against a specimen without defects, rather than as absolute values. It appears that:

- Configurations with defects ≤ 12 mm in diameter and up to three defects (nail, screw and bolt holes, and small knots) in all lamellae resulted in <6% degradation of the MOE of CLST in compression, whereas larger notches and knots, and larger numbers of defects introduced up to 21% degradation.
- The effect of defects that extended all the way through a board was only slightly more than that of those that did not.

- The MOE in compression of many bolt holes was 4% greater than that of a single notch with the same volume, i.e., several smaller defects appear to be less damaging than a single large defect.
- Knots perpendicular to the direction of the grain have a slightly greater effect on MOE than knots at 45°.

Introducing manmade defects appeared to have little impact on MOE in bending (Table 25). The largest degradation (2.7%) was produced by a single large defect at the centre of the span. A typical quantity of smaller defects, spread out along the length of boards, created a degradation of 0.9%, and when the same defects were concentrated on the centre of the span, degradation was 1.6%. As with the compression tests, defect volume concentrated in one area is more damaging to MOE than the same volume distributed over several defects.

Mechanically Jointed Beams Theory analysis of effects of lamella properties on CLST stiffness

As with the FEM, results are expressed as reductions rather than absolute values. Figure 36 plots the compressive stiffness for different configurations of CLST elements, whereby the compression stiffness values, $E_{CLT,x} k_c$, for each of the configurations have been normalised by dividing them by that calculated for 3-lamella CLT with no reduction in feedstock MOE (100% MOE). These normalised values are indicated by the symbol ‘~’, as $\sim E_{CLT,x} k_c$. Over the range of up to 30% feedstock MOE reductions investigated for CLST elements with the same overall thickness, it appears that:

- Reducing the feedstock MOE for both longitudinal and crosswise lamellae (“L+C”) leads to a maximum decrease in overall element compression stiffness of 30% (for a feedstock MOE reduction of 30% for all of 5 lamellae, with $L/d=30$).
- Reducing the feedstock MOE of only the crosswise lamellae (“C”) leads to a maximum decrease in overall element compression stiffness of only 5.5%.
- The compression stiffness of 3-lamella CLST is greater than that of 5-lamella CLPT and CLST with the same overall thickness, and this difference is more pronounced at a higher span-to-depth ratio.
- The compression stiffness of 3-lamella CLST exceeds that of 5-lamella CLPT for up to:
 - 6% feedstock MOE reduction of both longitudinal and crosswise lamellae, and
 - 30% feedstock reduction of only the crosswise lamellae.

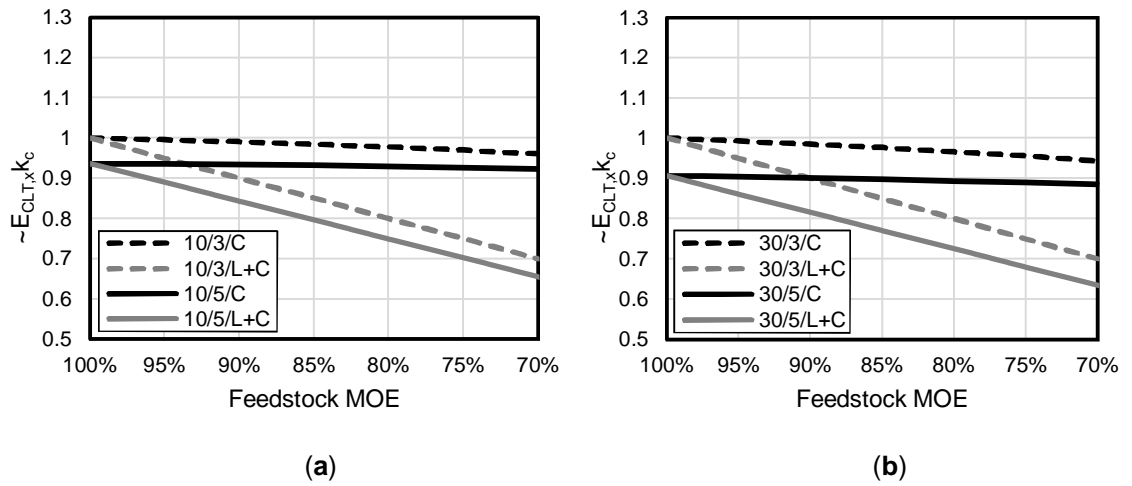


Figure 36. Normalised compression stiffness ($\sim E_{CLT,x} k_c$) for 3- and 5-lamella cross-laminated secondary timber with varying feedstock modulus of elasticity (MOE) reductions, of the longitudinal (L) and/or crosswise (C) lamellae, with (a) span-to-depth ratio, $L/d = 10$ and (b) $L/d = 30$.

Figure 37 plots the normalised bending stiffness for different configurations of CLST elements. It appears that:

- Reducing the feedstock MOE for both longitudinal and crosswise lamellae leads to a maximum decrease in overall bending stiffness of 35% (for a feedstock MOE reduction of 30% for all of either 3 or 5 lamellae, with $L/d=30$).
- Reducing the feedstock MOE of only the crosswise lamellae leads to a smaller reduction in overall CLST element bending stiffness, which is only 2.5% for the 5-lamella element with $L/d = 30$, but up to 14% for that with $L/d = 10$.
- Element span-to-depth ratio has an important impact on the results, with 5-lamella CLST having a greater bending stiffness than 3-lamella CLST for $L/d = 10$, and vice versa for $L/d = 30$.
- For $L/d = 10$, the bending stiffness of 3-lamella CLPT is exceeded by that of 5-lamella CLST with up to 18% MOE feedstock reduction of all lamellae.
- For $L/d = 30$, the bending stiffness of 5-lamella CLPT is exceeded by that of 3-lamella CLST with up to 10% MOE feedstock reduction of all lamellae.

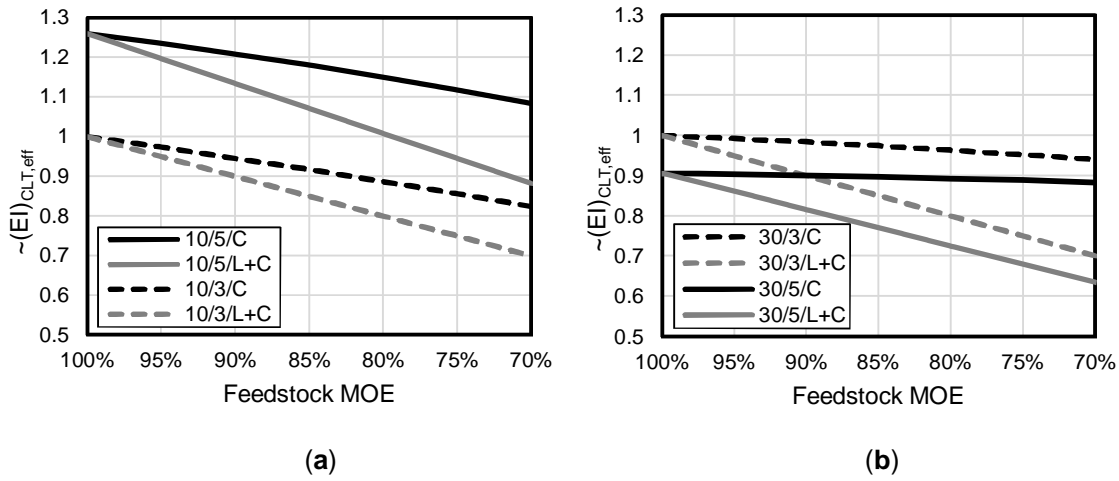


Figure 37. Normalised bending stiffness ($\sim E_{CLT,eff}$) for 3- and 5-lamella cross-laminated secondary timber with varying feedstock modulus of elasticity (MOE) reductions, of the longitudinal (L) and/or crosswise (C) lamellae, with (a) span-to-depth ratio, $L/d = 10$, and (b) $L/d = 30$.

Figure 38 shows the normalised 3- and 5-lamella bending stiffness as surfaces over the range of span-to-depth ratios and reductions in feedstock MOE of the crosswise lamellae. At $L/d < 18.5$, a 5-lamella element is always stiffer for a reduction in feedstock MOE of up to 30%, while at $L/d > 22$ a 3-lamella element is stiffer. In the zone $18 < L/d < 22$, CLST with either 3 or 5 lamellae may be stiffer, depending on the reduction of the feedstock MOE.

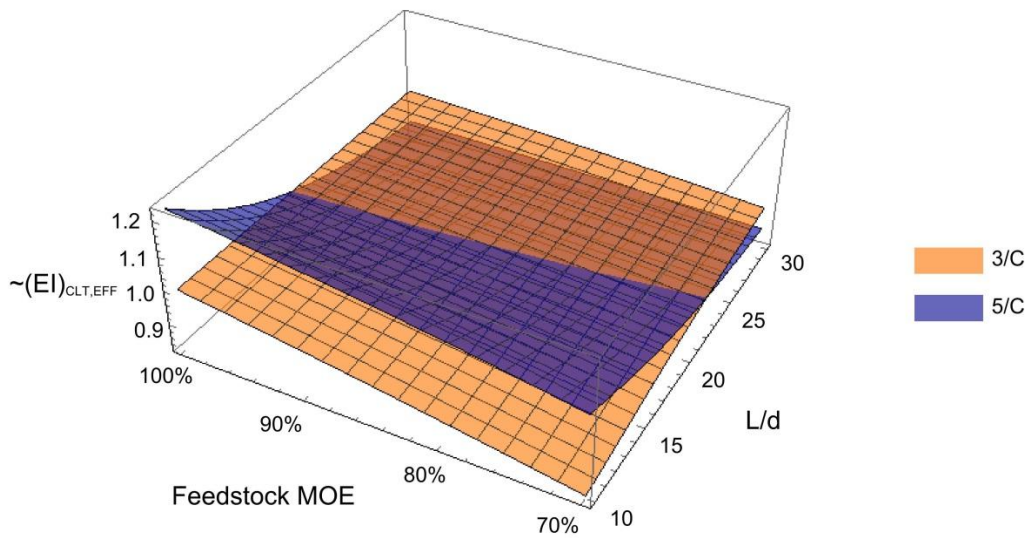


Figure 38. Bending stiffness of 3- and 5-lamella cross-laminated secondary timber elements with reduced crosswise feedstock modulus of elasticity (MOE), as a function of span-to-depth, L/d .

Implications, limitations and recommendations

Physical production of specimens in the UCL laboratory highlighted no fundamental constraints on the principle of upcycling secondary timber into CLST. Feedstock was easily sourced through existing reuse infrastructure; to support viable CLST manufacturing plants, this would need to develop holistically as a system comprising information about materials soon to emerge from demolition activities, procurement, reclamation and consolidation (Rose and Stegemann, 2018b, 2018a). Although trimming reduced yield considerably, in real-world practice, lamella thickness could be designed to optimise yield from the available feedstock.

The bending MOE and MOR of both CLST and CLPT were influenced by poor quality finger joints and delamination. These are attributable to the limited CLT production capability of the UCL laboratory. The limited size and capacity of woodworking equipment such as the circular saw, planer thicknesser, and hydraulic press meant that the number of specimens processed and dimensions of specimens were limited. As a result, scaling effects caused a disproportionate effect of finger joints and large defects on mechanical properties; e.g., a knot causing failure in one case had a diameter of more than half the specimen width. Similarly, a finger joint would not normally be the full width of the specimen. The lower MOR and higher MOE of CLST may be attributable to the greater number of finger joints necessitated by the shorter length of the secondary timber boards; however, greater stiffness and brittleness may also be an effect of ageing (Attar-Hassan, 1976) and requires further investigation.

In light of these constraints on experimental testing, FEM and MJBT are shown to be effective methods of preliminary research into the effects of a secondary timber feedstock. The FEM indicates that small defects like nail holes and screw holes, up to the concentrations found in a survey of secondary timber, would degrade MOE of CLST in compression, or bending, by less than 6% compared to a configuration with no defects. It appears that distributed defects are less degrading for the MOE of CLST than concentrated defects, and single large defects have greater impact than many small defects. This implies that attention should be paid to the identification and removal of sections of members that contain large or concentrated defects. This is a simpler process than condemning all members that have small, scattered holes (Brol et al., 2015), and could be expected to result in a larger yield of useable timber.

To address inconclusive current knowledge of the effect of ageing on timber and unknown histories of loading and climatic conditions, MJBT was used to assess the suitability of using secondary feedstock that may have a reduced MOE. The MJBT calculations suggest that it may be viable to use secondary timber with a reduced MOE for crosswise lamellae within CLT for compression elements (walls) or bending elements (floors) that have a large span-to-depth ratio without significantly compromising element properties. However, for bending elements with a low span-to-depth ratio, crosswise lamellae with a reduced MOE significantly reduce

overall section stiffness. *This is due to the quadratic relationship of the element length to the rolling shear of the crosswise lamellae when defining the fastener stiffness γ .*

The MJBT calculations also indicate that for bending elements, the number of lamellae that provides a stiffer overall section is dependent on the span-to-depth ratio. The interaction between the 5-lamella and 3-lamella configurations as a function of span-to-depth ratio provides the opportunity to optimise the specification of CLST based on the structural requirements and geometry of an element, and the resource drivers of a particular project. If material resource efficiency is prioritised (i.e., as much secondary timber is used as possible), then 5-lamella CLST elements with crosswise lamellae feedstock from secondary timber will be more favourable than 3-lamella CLPT. If fabrication resource efficiency is prioritised, then 3-lamella designs may be preferred to 5-lamella.

Arguably there is good potential to use high quality CLST containing a limited amount of high quality secondary timber in the crosswise lamellae as a replacement for CLT in most applications. There are also perhaps three situations where CLST produced entirely from secondary timber feedstock with a reduced MOE may be suitable: (1) specific elements where structural demands are low and a reduction in mechanical properties can be accommodated, such as single storey buildings, or for external or partition walls which are not considered part of the primary load-bearing or stability structure; (2) specific elements where an increase in element thickness and weight is not critical, such as structures on lower value land where the ratio between gross area and net area is not critical, or where the foundations are inexpensive; and (3) stocky bending elements in scenarios where material efficiency is prioritised over fabrication efficiency, and 5-lamella CLST can be specified as a stiffer alternative to 3-lamella section equivalents.

Currently, BS EN 16351:2015 (BSI, 2015) requires all timber for CLT to be strength graded or tested according to BS EN 14081-1:2016 (BSI, 2016a). Most European CLT production uses C24 graded timber throughout the section, as it is widely available, rather than because it is specified (D. Crawford et al., 2014). Thus high grade members are employed indiscriminately in lamellae that perform little structural function. Since the majority of CLT is produced for a specific application, it is possible to determine the extent to which its feedstock can be of a lesser grade. The present project applies this in the context of reusing secondary timber for environmental benefits. The findings may also have relevance to normal CLT production with a wider range of harvested timber, in pursuit of potential cost savings and environmental benefits.

Further research

As a pilot research project, the findings demonstrate the principle of CLST and stimulate further research questions to advance this concept towards commercial application through additional laboratory- and pilot-scale experiments and modelling:

- What are the properties and variability of secondary timber feedstock? How can these best be characterised for commercial-scale quality control?
- How does variability in the properties of secondary timber affect the variability of CLST stiffness and strength properties?
- Does physical testing bear out modelled findings on the effectiveness of various CLST formats?
- Is there any difference in the bond strength, dimensional stability, lamination, rolling shear and fire behaviour of CLST and CLPT?
- If the apparently greater bending stiffness of secondary timber in the experimental research is borne out over a larger population of secondary timber, and this is combined in CLST with primary timber that is less stiff but has greater bending strength, how does this influence panel performance? Can these contrasting qualities be complementary?
- To what extent does the performance of secondary timber correlate with density (of a whole member or of areas with defects)? Can defective parts of boards automatically be identified and removed, for instance through the use of non-destructive imaging techniques that are normally used in conservation of historic structures (e.g., Falk et al., 1990; Lechner et al., 2014; Riggio et al., 2015)?
- How is CLST performance affected by incorporating other parts of the wood waste stream (e.g., secondary plywood, OSB, particleboard, MDF; unused surplus timber from construction)?
- What are the projected quantities of secondary timber that will be available and useable in CLST in the future, and what is the most appropriate form of reverse logistics for harvesting feedstock?
- What is the cost of acquiring useable secondary feedstock relative to primary feedstock, and what scale of operation is needed to be commercially viable?
- Can conventional PUR and melamine-urea-formaldehyde adhesives be replaced with a non-toxic biodegradable alternative, or other joining technique (e.g., Brettstapel, friction-welding of wood; Buck et al., 2015; Hahn et al., 2014; Ramage et al., 2017a; Stamm et al., 2005; Wójcik and Strumiłło, 2014), for a product that is consistent with biological metabolism in a circular economy (Campbell, 2018; McDonough and Braungart, 2002)?

6.3.5 Conclusions

The concept of using secondary timber as feedstock for CLT was explored using complementary methods. The fabrication process and mechanical properties of CLST were tested in small-scale laboratory experiments, which showed no significant difference between the compression stiffness and strength of CLST and a control. FEM suggested that typical

minor defects in secondary timber have only a small effect on CLST panel stiffness in compression and bending. MJBT calculations to examine the potential impacts of secondary timber ageing on CLST panels found that this has little effect on compression stiffness if only the crosswise lamellae are replaced. Since use of secondary timber to make CLST has a more significant effect on bending stiffness, design using CLST will need to consider appropriate combinations of primary and secondary timber for specific structural applications.

More testing is needed to build upon this concept and generate a greater understanding of the characteristics of secondary timber and its properties within CLST. Commercialisation will also require consideration of other issues of sustainability, including the supply of secondary timber, and life-cycle environmental impacts of CLST production in comparison with CLPT.

6.4 Cross-laminated secondary timber realisation system and collaborating systems

6.4.1 Introduction to the enterprise realisation system

Section 6.3 (Rose et al., 2018) connected research that recognises end-of-life buildings as an underexploited stock of materials, with the emergence of circular economy thinking as a means of reducing the embodied impacts of building materials; and new research into alternative feedstocks for CLT. In doing so, it introduced a new area of future research. The paper presented a carefully evidenced proposal for the use of secondary timber in CLST.

If the proposal holds the promise of being technically feasible, then before going further with testing, attention turns to the practical feasibility of its implementation. This section places the material intervention of making CLST into the context of a notional enterprise realisation system (Martin, 2004). It does not claim to provide comprehensive answers to questions that may be better addressed in a business plan than a thesis; it gives an overview of operations and highlights areas for further investigation. Martin's systems engineering base model (introduced in section 3.3.2) is again employed; this time to represent the system of CLST and its context (Figure 39). A brief description of the elements of the model follows.

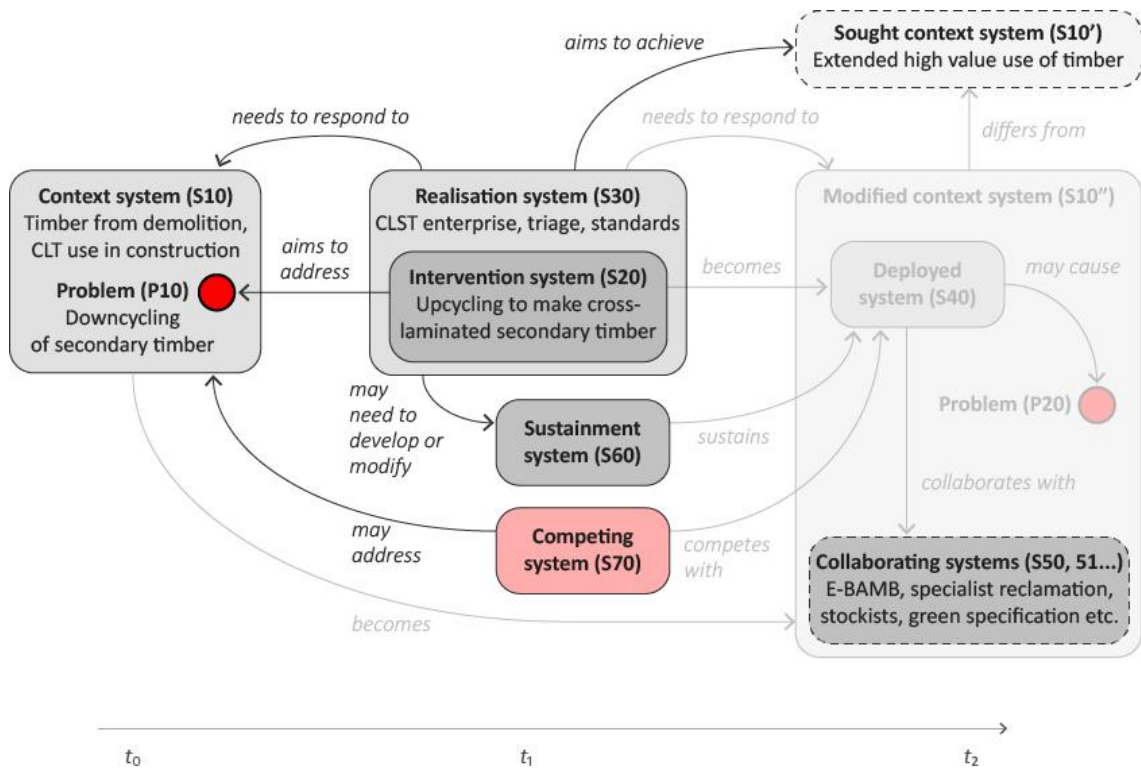


Figure 39: Systems engineering diagram for cross-laminated secondary timber (base model adapted from Martin, 2004). Subsystems that cannot be described at time t_1 are greyed out.

- Context system (S10): waste management of timber removed from the existing building stock through demolition; and the trend of CLT's increasing use in additions to the building stock, as described in sections 6.2.2 and 6.3.1.
- Problem (P10): premature downcycling and incineration of reusable timber, as described in section 6.2.2.
- Sought context system (S10'): transition to a scenario in which reusable timber is separated out for new repurposing and upcycling processes that extend the high value use of timber, avoiding or delaying the impacts of waste management, maintaining the material's store of sequestered carbon, and displacing the use of more impact-intensive construction materials, as described in section 6.2.3.
- Modified context system (S10'') is greyed out because only the sought context system (S10') can be described at time t_1 .
- Intervention system (S20): the core process of using secondary solid timber as feedstock for CLST, as described in section 6.3. Material processing steps that differ from CLPT are elaborated in section 6.4.2.
- Realisation system (S30): resources and capacities needed to carry out the process of upcycling timber into CLST. This is described in section 6.4.2 based on the potential

operation of a CLST enterprise within the triage described in Chapters 4 and 5 (Figure 40). In section 6.4.3, the economic viability of the enterprise is discussed.

- Deployed system (S40) is greyed out because only the intervention system (S20) can be described at time t_1 .
- Collaborating systems (S50): the capacities developed by the triage, as described in section 6.4.2, which could include access to E-BAMB information, specialist deconstruction and reclamation companies and designers looking to specify reused, repurposed or upcycled products.
- Sustainment system (S60): keeping the deployed system operational will require a continual supply of feedstock; premises, equipment and staff; and an ongoing market for its products.
- Competing systems (S70): organisations that could act as collaborating systems, such as reclaimed timber stockists and salvage yards, could also compete for timber that they sell for reuse or repurpose as furniture.

6.4.2 Potential operations and feasibility of a cross-laminated secondary timber enterprise

Logistical questions that arise about a CLST enterprise fall into four main areas: how does it identify its feedstock; how does it procure its feedstock; what is the process of turning its feedstock into products; and how do its products reach market? Figure 40 indicates how these operations could be achieved through sequences of triage activities. It divides those activities that could be undertaken by the CLST enterprise from those carried out by collaborating systems. This delineation is not the only one that can be conceived; nor is it fixed. For instance, the enterprise could, in time, integrate its own deconstruction team; or the harvest and consolidation function could be outsourced. Interfaces with other parties in the triage to address the four questions are discussed in the following subsections.

The analysis draws on findings from the researcher's experience of carrying out pilot production of two CLST panels for Chrisp Street Exchange (CSE; reported in a different light in section 5.4.3; see also Appendix R). It also draws on observations from visits to enterprises that act as precedents for different parts of the process: Hadfield Wood Recyclers (Appendix J-1); Community Wood Recycling Project,¹² a network of enterprises that gathers timber from C&D, consolidates and prepares it for reuse (Appendix J-2); Stora Enso's Austrian CLT factory (Appendix J-3); and InWood's UK glulam factory.

¹² <http://www.communitywoodrecycling.org.uk/>

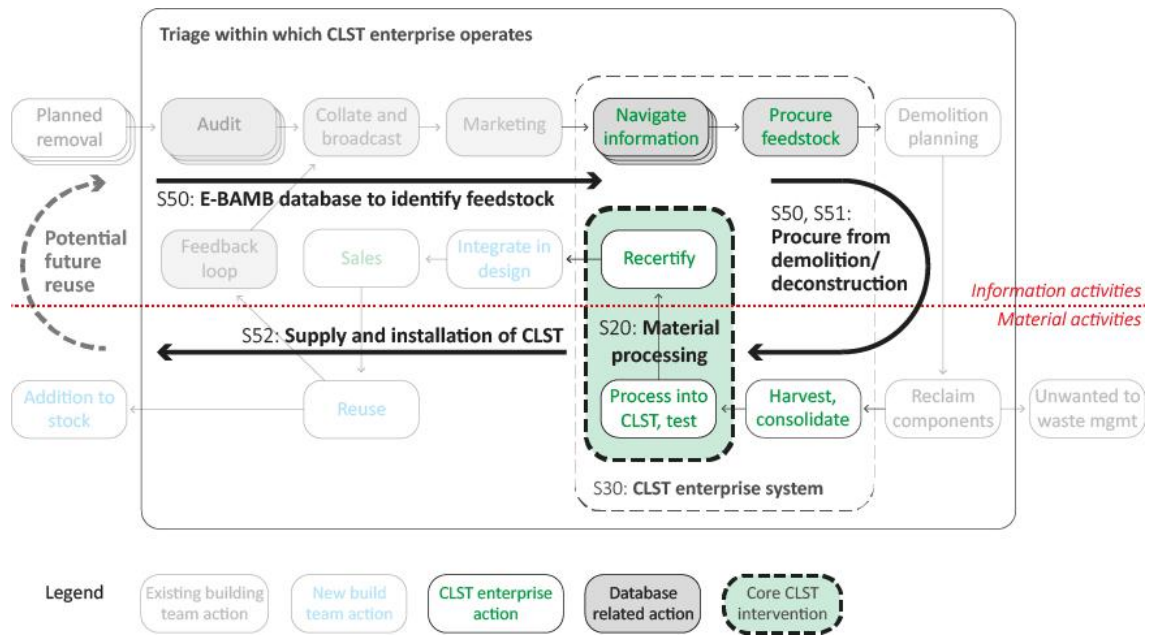


Figure 40: Triage diagram developed from Figure 13, showing interactions of cross-laminated secondary timber (CLST) enterprise system (S30) with other triage activities. The main sequences of activity leading to and from the enterprise are picked out with heavy black arrows (keyed to systems engineering numbering from Figure 39): identifying feedstock; procuring feedstock; processing feedstock; and supplying CLST.

Identifying feedstock

Collated, publicly available pre-redevelopment audits that identify future sources of secondary timber would assist in both assessing the feasibility of a CLST enterprise and operating it as a business. Construed as an E-BAMB database (section 5.2), this would act as a collaborating system to the CLST enterprise, allowing the entrepreneur to search forthcoming demolition projects for different types of timber element by time and location, to establish potential suppliers.

In the absence of a system of E-BAMB information generation, the extent of feedstock availability may be estimated by referring to previous years' statistics on waste wood published by Defra and reports commissioned by WRAP (see Appendix S). However, these are released infrequently and retrospectively; they are based on broad assumptions; and they do not contain qualitative description to allow the material's suitability to be considered, beyond, occasionally, the distinction of clean solid wood, treated solid wood and panel products. Based on the published statistics, Appendix S estimates that the amount of UK solid wood arising from demolition may be in the region of 0.6 Mtpa. Appendix T then discusses allowances for unsuitability of materials, inaccessibility and wastage that could lead to approximately 6% of this total (37,000 tpa) ending up as finished CLST. This would provide the structural materials for 3,700 homes. The aggregated totals thus allow some assessment of viability, but do not permit confidence in the volumes that are actually available and suitable; nor do they help the potential entrepreneur to pinpoint sources of secondary timber. This would instead have to be

accomplished by contacting waste management companies or making unsolicited approaches to contractors and demolition contractors.

Accessing feedstock

In the current situation, the simplest way to access timber feedstock would be to form agreements with waste management companies running WTSs that already receive and consolidate timber from construction sites. These companies pay to send materials to timber recyclers; the CLST enterprise could be an alternative destination. However, by the time the timber reaches the WTS, it is likely to have sustained damage and potentially contamination with other wastes (section 4.2). The enterprise would have no control over the condition of its feedstock and timber from many different sources would be mixed together.

A second option, but one which is not yet widely available, would be to partner with specialist stockists of secondary timber. Community Wood Recycling Project (CWRP; Appendix J-2) is a UK example of such an enterprise. It competes with waste management companies for C&D wood waste, offering contractors a cost-neutral alternative to the skip that promises to maximise reuse (nearly 50% reused in 2017) and create local employment. The head office in Brighton maintains relationships with nationwide contractors and developers, whose projects in different parts of the country are linked to local CWRP franchises. Their reverse logistics process seeks to avoid damage to timber: they provide a fenced enclosure instead of a skip on site, and attend site to load timber into a cage truck by hand.

The triage could be expected to increase the capacity of networks like CWRP by improving visibility of demand for secondary materials and increasing deconstruction. If a greater proportion of total wood waste was then reclaimed for use as solid timber and consolidated by networks like CWRP, a CLST enterprise could form an agreement to source feedstock. Alternatively, CWRP could extend their current activities (of preparing for reuse and some remaking into furniture and smaller objects) to include more ambitious manufacturing of CLST; or a CLST enterprise could go further and integrate soft strip or deconstruction services and material consolidation into its operations. This was the approach taken in the CSE pilot production. It allows greater control over the condition of the feedstock but adds logistical complexity to the business.

Material processing and recertification

There are many sub-processes to the core activities of the CLST enterprise. They can be summarised as turning incoming materials into useable feedstock; fabricating CLST; use of by-products; and testing and certification.

A collaborating Master's student investigated strength grading and the removal of common types of contaminant from secondary timber to produce material that is ready to be used in fabrication (Tiu, 2016; Appendix J-4). This study identified non-destructive acoustic grading as

an efficient means of determining the strength class of timber, the species of which is unknown. Further research could interrogate its use for secondary timber by validating the acoustic grading results with destructive testing of samples. This was the approach taken by Crawford et al. (2012) to assess the suitability of an acetylated timber product, which had unknown structural properties, as feedstock for glulam. They concluded that acoustic and visual sorting is adequate to select members for use in structural applications.

Timber that is of a suitable strength class for use in a CLST section would need to be made free of contaminants. Tiu (2016) proposed a sequence of processes to identify and remove chemical treatments, surface treatments, metal fasteners and other materials that may contaminate secondary timber. For instance, metal detection and existing 'nail kicker' technology could be combined to automate the removal of nails. In the pilot production for CSE, nails were pried out manually with claw hammers, reaching clear boards at a rate of around 1.7 linear metres per minute. Ensuring that no metal remains in boards is crucial to avoid damage to equipment. Further research would investigate the effectiveness of different manual and automated options for metal removal.

Once clean, graded timber has been produced, boards would be ripped down lengthways if necessary (e.g., to remove profiles and achieve right angled edges), sorted into nominal thicknesses (e.g., 20 mm, 32 mm, 44 mm), then, within each group, planed to consistent thicknesses. At this stage, areas of board that contain significant defects can be identified and removed by cross-cutting. In the pilot production, there was considerable wastage from ripping down and planing (Table 27), due to the architect's specification of narrower board widths and a panel thickness aesthetically appropriate for use as a table top. In industrial production of a structural component, board widths and lamellae thicknesses would be designed to maximise yield. Also due to the pilot project's aesthetic demands and the functional requirements of using CLST as a table top, far more timber was reclaimed than was needed so that boards with the fewest knots and other defects could be selected. Close to half of total board length was rejected as offcuts or unused boards, leading to a final yield below 30%. If a board section size of 100x18 mm had been chosen for this feedstock, and boards had been selected on the basis of structural soundness but not aesthetic factors, an end yield in the region of 60-70% could have been expected. Having reduced boards to workable section sizes, the fabrication of CLST panels would follow the same sequence of processes as CLPT: end-to-end finger jointing; edge-bonding to form lamellae; face-bonding lamellae and pressing into panels; and trimming and finishing.

As the by-products of the pilot project were various forms of clean timber, it was possible to donate sawdust to a local community garden and collect small and damaged offcuts for fire wood. Unused but sound boards were left to the Remakery for reuse in other projects. At industrial scale, the enterprise could seek opportunities for other products made from solid timber that is not suitable for CLST (e.g., Figure 68 in Appendix R); it could also integrate the

manufacture of panel products to minimise the quantity of material that leaves the factory as waste.

Table 27. Measured production yield in CLST pilot project for Chrisp Street Exchange.

Process	Volume (m ³)	Process yield (%)	Cumulative yield (%)	By-products
Stock of reclaimed timber (120x20 mm tongue and groove floorboards)	0.50	100.0	100.0	n/a
Ripping down to 90 mm width	0.40	80.4	80.4	Solid timber strips approximately 8x8 and 8x6 mm
Planing to 13.5 mm thickness	0.27	67.5	54.2	Wood shavings and sawdust
Cross-cutting and rejections	0.15	56.7	30.7	Solid timber offcuts with some splits, shakes, large knots, etc.
Belt sanding lamellae and trim to final size	0.14	92.1	28.3	Sawdust and solid timber offcuts

For adoption as a structural component in mainstream construction, CLST would need to gain the confidence of specifiers, contractors, clients and insurers. As discussed in section 2.4, certification and the provision of warranties is the normal way to generate this confidence. Mechanical properties are of the foremost concern for a structural product; section 6.3 began the process of testing CLST and set out the next steps. However, European Standard BS EN 16351:2015 (BSI, 2015) specifies other characteristics that would also need to be proven, including fire separation, spread of flame, dimensional stability and durability. Whether and how these properties differ from CLPT are subjects of further research. Establishing quality protocols to ensure that end-of-waste criteria are met could help to encourage the widespread development of CLST manufacturing.

Supplying cross-laminated secondary timber to the market

The existing CLT market is dominated by several very large manufacturers. The four biggest manufacturers made up two thirds of total production by volume in 2011 (D. Crawford et al., 2014). These companies have invested in heavily automated factories and have developed great economies of scale. Given this context, direct competition on price would be challenging for a new market entrant; however, CLST could be differentiated from incumbents in a number of ways to open up new market segments. Firstly, the use of secondary timber and the attendant social, environmental and economic benefits may act as incentives to some specifiers, contractors and clients. Secondly, smaller panel dimensions could potentially allow CLST to be installed on sites where the use of a crane is not feasible. Thirdly, the application of DfD principles such as modular panel sizes and reversible fixings could potentially allow for adaptability and deconstruction. Coupled with material passports and BIM integration, this

would help the components to retain their value at end-of-life, which has particular relevance to buildings with a known lifespan, buildings that are likely to change function over their lifespan, and to any client with a long-term financial interest in the site. Lastly, a smaller-scale operation using a range of different secondary timbers could offer a more tailored approach towards the appearance of the panels, potentially working collaboratively with designers to develop finishes for exposed CLST that are bespoke to projects.

Enterprises upcycling materials accessed through the E-BAMB database should also feature on the database as suppliers. LCA data generated in support of an Environmental Product Declaration (EPD) under BS EN 15804:2012 (BSI, 2014c) would be made visible to specifiers. If a quantity of CLST is proposed for a project, life cycle metrics, including volume and impacts of waste prevention, could be computed as part of the ‘feedback loop’ element of the database, allowing designers to make informed comparisons against other options and report back to clients. This function would allow the embodied carbon savings of CLST to be registered and potentially to contribute as an ‘allowable solution’ to meeting zero carbon targets (Battle et al., 2014), or to any future regulation of buildings’ embodied carbon impacts.

6.4.3 Discussion of economic viability

A top-down estimation of secondary timber quantities arising from demolition and the volumes of CLST production to which it could give rise suggest that the size of the business opportunity in various parts of England is significant (Appendix T). The question of economic viability comes down to whether there are adequate operating margins between the unit cost of accessing feedstock and the unit price the market will bear for the CLST product. This section does not attempt a detailed financial analysis: the cost of waste disposal and price of materials are volatile; costs vary geographically; and owing to its novelty, many of the operational costs are unknown and will require further research. Instead, this section defines the cost model and identifies ways that it can be influenced to increase the viability of a CLST enterprise.

A model can be used that is similar to one developed by Dunant et al. (2018) to assess the relative costs of supplying reconditioned and new structural steel. The formulation is altered to suit the parties and processes involved in CLST. A CLST company that buys its feedstock off a reclaimed timber stockist such as CWRP has a cost to produce a CLST element C_i :

$$C_i = F + D + P + t \quad (6)$$

where,

F is the price of secondary timber feedstock,

D is the supplementary cost of deconstruction over demolition,

P is the cost of processing, testing and certifying, and

t is the cost of transportation and handling.

In the case of CWRP, the costs of storage and the first stage of preparing the timber for reuse, i.e., removing nails, are within the operating margins of the stockist, so $F > 0$. Alternatively, a CLST company that collects its feedstock from demolition sites, and is paid a fee for managing contractors' timber waste (i.e., $F < 0$), has a cost to produce a CLST element C_{ij} :

$$C_{ij} = F + D + S + P + T \quad (7)$$

where,

S is the cost of storage and preparing the timber, and

T is the increased cost of convoluted transportation and handling.

In either case, the CLST enterprise has to sell its product for a market price M that is greater than C . The profit margin would need to be large enough and certain enough to justify the capital investment in premises and equipment. Given the present lack of industrial-scale upcycling processes, the equation may be financially unfavourable in most cases at present, but drivers that could affect each term are discussed.

The price of feedstock F fluctuates and is determined by the market. In Equation 7, the waste management fee that the CLST enterprise can command will, at best, match the market price of waste management. The enterprise may have to undercut incumbents to win contracts and to compensate the contractor's additional administration if, for example, the timber collection increases the number of parties attending site. The environmental credentials of having their timber harvested for upcycling may in some cases provide motivation for contractors to switch; or that incentive could be embedded in the process through, say, environmental accreditation schemes or more nuanced waste diversion targets.

There will be no supplementary cost of deconstruction D if the enterprise can use timber in the condition it normally arises from the demolition process. For many existing structural timber components, though, demolition involves the use of large plant, and members rarely avoid sustaining damage. The CLST enterprise would need to compare the additional cost of deconstruction to the impact of a reduction in yield if material is sourced from projects that proceed with typical demolition.

The relationship between the cost of processing, testing and certifying P and the market price M is the crux of value-adding achieved through upcycling. All of the costs that make up P would need to be scrutinised by the CLST enterprise. There may be different uses of timber not considered in this thesis that minimise P , add more value to M and achieve equal or better social and environmental outcomes. The ongoing discovery of competing uses for materials can give rise to positive progress; responsible policy would seek to frame the cost context so that environmental, social and economic gains are aligned. For instance, the cost of testing and certification may be manipulated by making it simpler or more arduous to achieve certification for secondary materials. Major CLT producers rely on purpose-built machinery, but a CLST

enterprise could plausibly be less automated and more reliant on manual labour. InWood, a successful glulam manufacturer in East Sussex, near London, uses a combination of automation and, for instance, hand-marking of faults in feedstock, manual transfer of boards from one conveyor belt to another and manual loading of presses. This case indicates that there are situations in which a greater level of manual labour can be made to work financially, but the extent to which such social benefits can accrue depends to a large extent on the price of labour. Policymakers' have a certain amount of control over this through tax policy; for instance, there could be VAT relief on the labour involved in disassembly, reprocessing, testing and recirculation of goods (Aldersgate Group, 2018; Stahel and Clift, 2015).

The previous section proposed ways that a CLST enterprise could develop new markets rather than competing on a like-for-like basis with major European producers, and potentially maximise their market price M . Prices of construction materials generally are likely to rise in a carbon or resource constrained future or if, say, trade tariffs on imports increase. This could have the effect of increasing the price that CLST can command. Making embodied carbon an allowable solution in zero carbon targets would be a beneficial policy mechanism. By allowing embodied carbon savings to reduce amounts currently payable in London through the levy for 'unavoided' operational carbon emissions (GLA, 2017: 326), it would give embodied carbon savings an economic value. In turn this would enhance the commercial benefits of secondary use of materials, like CLST, and nudge demand away from primary resource use. Developers who lag behind on using materials with low embodied carbon would, to some extent, be subsidising innovative manufacturers of low embodied carbon products. At present, a building that requires high operational energy hurts its owner through high running costs. A building with high embodied carbon is not necessarily any more expensive than one with low embodied carbon, and may indeed be considerably cheaper. Embodied carbon as an allowable solution would begin to address this problem.

A CLST enterprise would need to minimise the cost of storage S and of transportation T ; they are functions of land value, density of feedstock availability, and analysis could determine optimal locations. This also emphasises the importance of planning policy that seeks to retain land designated for waste management and industry close to sources of waste, and close to demand for construction materials.

The supply of construction materials is an extremely competitive market and many of the drivers that would incentivise the production of CLST do not yet exist. Each of the terms in Equations 6 and 7 is an area for further investigation; once carried out, the equations can be populated with data and conclusions can be drawn on the viability of CLST in different contexts and with different approaches. The assessment has drawn attention to ways in which the economic prospects of a CLST enterprise might be improved.

6.5 Conclusions and further research

The construction industry's consumption of raw materials creates environmental degradation, and the GHG emissions associated with producing and delivering building components will need to be reduced to meet legally binding targets. The industry creates significant volumes of waste wood, much of which has residual quality and value that dissipates in conventional waste management processes. Extending the lifespan of timber creates GHG benefits, but this may be of modest significance if it replaces the use of primary timber (Sathre and Gustavsson, 2006; Werner et al., 2006). Greater benefits come about where a secondary resource can perform a duty normally performed by a material of greater environmental impacts (Geyer et al., 2015). Transforming secondary timber into a structural product is an example of targeting a demanding duty that can be performed over a long period of time: enhancement of components' performance, as set out in Chapter 1. To realise this potential, it must be feasible for practitioners to employ repurposed or upcycled product in place of primary resources. This chapter makes a preliminary step towards that goal in the case of CLST.

CLT is gaining acceptance as an alternative to structural steel and concrete. This chapter investigated the environmental implications of including secondary timber in CLT, in comparison to existing timber waste management and typical concrete, steel or CLPT construction. To investigate the technical implications of the concept, it compared the mechanical properties of CLST and CLPT, surveyed common timber defects and analysed their effect on CLST, and calculated the performance of combinations of primary and secondary timber in various configurations. No fundamental constraints to the principle were discovered. The practical feasibility of producing CLST and the notional enterprise that would carry out the process were assessed in the light of the earlier chapters' models of urban component management. This highlighted how an upcycling enterprise and other parties undertaking activities within a triage could act together to separate out and recirculate reusable components. A cost model for the enterprise was developed and its economic viability was discussed. Structural changes to the economic context that are likely to come about in a carbon or resource constrained future were identified alongside other potential levers to increase the viability of CLST and similar business opportunities.

The proof of concept study suggested areas for further research, as noted in section 6.3.4. Primary amongst those suggestions is the need for a more thorough understanding of the characteristics of secondary timber. The scientific community has not reached a consensus on the effects of timber ageing. The effect of timber's natural variability (an individual tree's growing conditions; different species; different regions) appears to be multiplied by the variety of ways in which it can age, and multiplied again by the variety of applications and conditions of its use. The challenge for reuse, including in CLST, is to gain an adequate understanding of the residual properties of timber, the history of which may be largely unknown. Further research must address means by which secondary timber can be regraded. In the proof of concept, it was suggested that CLST made entirely from secondary timber could be used in a few limited

circumstances. This is a sensible, cautious approach; however, if secondary timber can be regraded reliably and efficiently, it may be possible to expand upon these applications. A grading system could feed into new standards for the design of CLST sections; manufacturing processes can then be developed that demonstrate consistency of performance under a viable testing regime.

Other performance criteria such as fire separation, spread of flame, bonding strength, dimensional stability and durability require investigation to examine whether and how CLST differs from CLPT. The stages involved in producing useable feedstock from incoming secondary timber need further analysis from a technical and financial perspective. The costs of all aspects of a CLST enterprise's operations need to be investigated in detail. Once there is a greater understanding of the processes that would constitute viable CLST production, LCA could be pursued to compare CLST to current treatments of waste wood (with a functional unit of a quantity of waste wood); or to increase the robustness of Zou's (2017) comparison of CLST and CLPT.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Synthesis of urban- and enterprise-level systems engineering

A reasonable challenge to the proposals made in Chapters 4 and 5, which the researcher has faced in presenting the work to various audiences, is that discarded materials ‘just aren’t any good’. There is a sense that nothing more can be done with C&D waste: that the salvage yards and industry already do what is possible; that a product made out of waste will not be suitable for mainstream use; that no business case can be made. A claim made in the urban-level research presented in this these is that there *are* ways of adding value still to be discovered, and this process of discovery can be facilitated by the systemic proposals put forward in Chapters 4 and 5.

The example of CLST demonstrates the existence of a practical and environmentally preferable use of discarded components that is not currently being implemented by industry incumbents. New opportunities may arise from developing technologies, such as engineered mass timber; or they may come into view with knowledge of materials arising from the existing building stock, having hitherto been overlooked. The researcher was able to propose a new use for secondary timber through awareness of the extent of that waste stream and of trends in construction that make the product marketable. This awareness came about through the doctoral project but could be made more generally accessible through the collation and broadcasting of E-BAMB information. The emergence of the idea of CLST, from only one person contemplating partial information about available materials, suggests that with many more minds and more comprehensive E-BAMB information, far more practical ideas could emerge.

As well as increasing the likelihood of idea emergence, the case of CLST shows that E-BAMB information and other collaborating systems in a triage enhance the feasibility of enterprises to commercialise them. A prospective upcycling enterprise would be aided by the capacities afforded by the triage. The E-BAMB database allows it to assess the scale of the opportunity and pinpoint sources of feedstock; networked deconstruction specialists and stockists help it to access feedstock efficiently; visibility of its products to specifiers and contractors help to facilitate sales.

7.2 Contributions and findings

This thesis makes three main contributions to knowledge. Firstly, it diagnoses mechanisms that may be producing the construction industry’s reliance on waste management, and explores the alternative notion of ‘component management’. This challenges the assumption that components removed from the building stock must either be: a) directly reused, which can often be impractical, and is rarely given due attention, or b) sent to waste management, which wastes embodied impacts. Instead, the role and implementation of repurposing and upcycling are

described, alongside a procedure for more comprehensive examination of opportunities for direct reuse. Taken together, these three types of process – reuse, repurposing and upcycling – articulate the breadth of options for retaining and enhancing existing building components' performance and value.

Secondly, the thesis develops an urban-level 'triage': a sequence of activities to separate out components for reuse, repurposing and upcycling, from those for which downcycling or energy recovery are the best option. A key element in the triage is an information system; the thesis reviews current means of understanding E-BAMB and presents a new approach to gathering this information. The triage connects this information to the wider processes of building procurement. It helps to facilitate the emergence of new ideas for the use of components from the existing building stock and supports organisations in implementing such ideas. It is also applicable to the future building stock. Circular economy strategies could deliver new buildings with, say, leased and tagged products with comprehensive material passports. When these reach end-of-life, they will still rely on systems for reuse, repurposing and upcycling in the event of original manufacturers going out of business, or components no longer serving the purpose for which they were originally intended. The contributions to urban-level systems thinking are complementary to other circular economy strategies.

Thirdly, the thesis proposes an innovative manufacturing process using secondary timber in a new product: cross-laminated secondary timber. This provides an exemplar case study of the principle of industrial-scale upcycling. The potential environmental impacts of the intervention are discussed. A proof of concept study is presented, with a preliminary examination of technical feasibility and specific research questions to drive the concept towards, ideally, future pilot- and commercial-scale implementation. Engineering the system of a notional CLST enterprise shows how it would identify and procure feedstock, turn feedstock into products and take its products to market. The discussion highlights the collaborating systems that would help the CLST enterprise to operate, wider changes that would increase its economic viability, and directions for further investigation.

As well as an academic and, plausibly, a practical contribution to improving the use of secondary timber, the case of CLST illustrates one of the central tenets of component management by helping to define upcycling. It demonstrates what can now be described as a *process that transforms secondary materials, such that the resulting product has the potential to perform a duty normally performed by a material of greater environmental impacts*. In each case, a speculative upcycling idea must be tested for the relative impacts and feasibility of the process and the potential of the product to be deployed in practice. The investigation of CLST pursued in this thesis provides a template for investigation of other prospective upcycling processes.

7.3 Implications and recommendations

7.3.1 Policy

The urban-level research shows that organisational changes are necessary to draw together a sequence of activities – a triage – that would enable reuse, repurposing and upcycling. It is recommended that:

- Policymakers stimulate the generation of E-BAMB information at early stages of projects by requiring the submission of a pre-redevelopment audit for all developments, above a certain size threshold, seeking planning consent.
- Local authorities or service providers develop, maintain and promote an E-BAMB database in which the audit results are collated and broadcast.
- A quota of reused, repurposed or upcycled components to be sourced through the E-BAMB database, or from the existing salvage sector, is stipulated in public procurement to build capacities with a view to subsequent use of this procurement route by any client and specifier.
- Local authorities allocate pockets of publicly owned land and resources to manage intermediate storage and consolidation of components for limited time periods.
- Suppliers of reused, repurposed or upcycled materials are required to provide embodied carbon data, with a view to savings against benchmarks being allowed in projects' zero carbon targets or included in future regulation of buildings' whole life carbon.
- VAT relief is introduced on the labour involved in disassembly, reprocessing, testing and recirculation of secondary goods.

There is great potential to improve upon current use of building components removed from the existing building stock, but the services involved tend to be labour-intensive, and thus expensive. The last recommendation begins to amend the situation but higher level structural reform must be the longer term goal. Shifting the balance of taxation away from labour and other renewable resources and onto extraction or consumption of non-renewable resources, generation of waste and carbon emissions, would be of inestimable benefit to existing and emerging enterprises pursuing resource efficient business models.

7.3.2 Practical action

Establishing a system of component management presents major benefits to local, national and the global economy in terms of avoiding loss of value, creating local employment and reducing the environmental burdens of the construction industry. It also presents benefits to organisations that own building stocks and manage ongoing processes of refurbishment and

regeneration. Poplar HARCA is a particularly good example of a housing association engaged in demolition and construction on sites that are within close proximity of one another, and with networks of residents and local businesses that are likely to have need for materials discarded from the major projects. To apply the research findings in this context, without the benefit of the policy interventions recommended in the previous section, the proposed triage activities may be streamlined to the following fundamental steps:

1. Audit: carry out photographic audit soon after it has been confirmed that a demolition or soft strip is to go ahead (e.g., on receiving planning consent).
2. Broadcast: release audit information (e.g., via an organisation-wide E-BAMB database) to the design teams of all the organisation's projects, other projects that they wish to support, local businesses and community groups.
3. Navigate information: potential recipients search audit information and consider potential new uses.
4. Procurement: alert supply project participants of interest from potential recipients; open communications between parties.
5. Reclamation: depending on timing and on the component type requested, either reclaim in advance of demolition, or write into tender documents; collection or delivery to recipient site.
6. Feedback loop: measure financial, environmental and social value of reuse; potentially establish benchmarks for reclamation that future projects have to report against.

This is a simple triage process that any organisation managing a large portfolio of buildings could implement to create the possibility of building components being diverted from waste management and instead reused. It will tend to benefit smaller construction projects, local businesses and community projects, which have lesser demands than the mainstream construction industry. The industrial sponsors – and housing organisations more generally – can adopt this process in seeking to retain the value of existing building components in their local area, and to realise social and economic benefits.

For reclaimed components to re-enter the mainstream construction industry and displace primary production, bringing more significant environmental benefits, some or all of these additional steps will be required:

- Consolidation: storing and managing an inventory of components to ensure adequate quantities for larger projects;
- Processing: adding value to a secondary feedstock and readying it for adoption;
- Testing and recertifying: demonstrating adequate quality to ensure safe, insurable use.

These actions imply the need for intermediary businesses. An example investigated in this thesis is a CLST enterprise. Based on the research presented, steps could be taken to implement the idea of CLST. Initially this should be for non-structural applications. Identifying and accessing feedstock, streamlining the core steps of material processing, and establishing markets for the product, are all areas of practical action that could progress while the evidence to support its use in structural applications is developed.

7.3.3 Areas of further research

Urban systems for component management

To increase confidence in the case for introducing the proposed policies, further research should assess the magnitude of adoption that they could be expected to produce and attempt to quantify the benefits. The potential of reuse, repurposing and upcycling to reduce disposal costs for waste generators, and reduce material costs for new construction, should be considered alongside an assessment of environmental and social value. In systems engineering terms, the 'deployed system' and its impact on the 'modified context system', including any unintended consequences, are still to be investigated. This project has assumed that secondary components will be adopted if they meet clients', specifiers' and contractors' need for certainty over quality and quantity, and do not incur a cost penalty. Further research could investigate whether there are other criteria for adoption that could emerge as additional constraints.

The E-BAMB information system will require design development to become operable. Research topics include the ownership and maintenance of the database (the 'sustainment system') and its interface with BIM-enabled specification. At present, a user of an RMM platform uses written search terms or an item category structure to search for the item they need, and either finds it or does not. Development of search technology to allow users to navigate components' *qualities* within a large dataset could facilitate the identification of unexpected solutions to needs.

Cross-laminated secondary timber

The CLST proof of concept study provoked a series of research questions, as noted in section 6.3.4. To take the concept forward to pilot- and commercial-scale implementation, there is a need for a more thorough understanding of the characteristics of secondary timber. Further research must address means by which secondary timber can be regraded. The mechanical and other properties of the CLST product must also be better understood. The modelled findings on the effectiveness of various CLST formats require verification through laboratory testing. The stages involved in producing useable feedstock from incoming secondary timber could be taken up through practical action, but specific topics such as the use of technology to identify and remove fixings and defects may require industrial research. The costs of all

aspects of a CLST enterprise's operations need to be investigated in detail. With greater understanding of the production process of CLST, more thorough assessment of socio-economic and environmental sustainability can follow.

Innovation in component repurposing and upcycling must look for ways to extract greater performance from secondary resources. Creativity is a crucial element in identifying new uses or value-adding transformation of components; then it must be made feasible for practitioners to employ them in place of more impact-intensive primary resources. It is hoped that this orientation to secondary materials, exemplified by the case of CLST, is taken up by other researchers and applied to other material groups.

Future direction of research on waste and material use in the construction industry

Advances in the design of additions to stock, management of existing building stock and management of building components removed from stock are all valuable and all contribute to moving the industry in the direction of sustainability and resilience. The current swell of interest in circular economy strategies that are concerned with the design of new additions to stock should not distract from the need to develop systems for building components from both today's existing stock and from that of the future. Nor should the multifarious aspects of the circular economy detain researchers at a level of investigation that seeks to address the entire question of a 'circular construction industry'. There has been a valuable period of coming together as researchers in various areas united under the common banner of 'circularity'. Further development at the forefront of each sub-realm (e.g., repurposing of glass; the E-BAMB information system; the deployment of material passports; reuse of structural steel; scan-to-BIM technology; upcycling of timber; etc.) now seems the most pertinent route to progress.

7.4 Research quality

In section 3.5, the research quality criteria of 'trustworthiness' and 'authenticity' were discussed and combined with complementary criteria to develop an assessment framework appropriate to the research (Table 11). This section uses the framework to reflect on successes and challenges in the practical implementation of the research design (Table 28).

Table 28: Application of framework for assessing research quality (adapted from Bryman, 2012: 390-6; Guba and Lincoln, 1994; Tracy, 2010; Yardley, 2000).

Criteria	Guiding questions	Response
Relevance	Is the rationale behind the research made explicit, and is it compelling? Does the research question the status quo, and does it contribute to the field?	<p>The extent of impacts of the construction industry is discussed to show a compelling need for change. Three areas of attention to address the stated problems are reviewed in Chapter 1; the thesis explains the benefits and limitations each. A case is built up for the focus on ‘components removed from stock’, though it appears likely that improvements in all three areas will be needed, and they can make complementary contributions to the sustainability and resilience of the built environment.</p> <p>The research questions the status quo of C&D waste management, challenging the way it is organised at the level of a municipality, and proposing interventions to create change. It questions the status quo of wood waste management, suggesting a specific process to create change.</p> <p>Contributions to the field are demonstrated by the two publications in peer-reviewed journals and third publication under review. The researcher is not aware of other work that coordinates so many facets of the reuse of existing building components, or that derives an enabling intervention and explores key subsystems in detail.</p>
Credibility	Is the adopted methodology explained in sufficient detail to allow the logic of the research design to be assessed? Is the risk of error reduced by adopting a pluralist research approach based on multiple perspectives?	<p>The methodology is explained in Chapter 3, based on a recognised model for the conception of research design. The logic is explained in layers from research paradigm down to data collection and analysis.</p> <p>Exposure to error was reduced by opening the research to ‘communities of enquiry’ on three fronts: learning from practice and presenting back to practitioners; engaging a wider academic community at UCL and participating in conferences, academic workshops and going through peer review processes; and presenting findings to the wider public.</p> <p>The initial set of case studies built up an understanding of the existing context using triangulation of sources, including interviews with a range of stakeholders. Multiple projects were used for the live case studies, bringing in the perspectives of designers, businesses and an artist as well as main contractors. The case of CLST lent the researcher the viewpoint of a prospective entrepreneur considering a business opportunity; it also brought together different academic perspectives through the input of Master’s students and the view of a practising engineer. CLST was presented to hundreds of members of the public at the Victoria & Albert Museum; a video about the project by Yushi Li¹³ (Appendix I-3) has had more than 5,500 views on YouTube.</p>
Transferability	Are context, methods and findings described in sufficient detail to allow future researchers to consider transferability of research to a new setting, and to carry out similar research processes?	<p>The research context, specific methods adopted in empirical elements of the research, and the findings, are explained in detail in the relevant thesis sections and appendices. Rich descriptions of the proposed triage activities and their application in projects allow other researchers to test them in other contexts. The limitations of the research are explained.</p> <p>The case of CLST demonstrates a way of using the triage to generate new ideas for secondary use. The creative process of ideation resists description but an account of the circumstances of CLST emergence has been provided, to allow the possibility of transferring this thinking to other material groups. The principle of combining small parts into a larger composite may be transferable to other discarded materials.</p>

¹³ https://www.youtube.com/watch?v=r0Eiq_4GXEA

Criteria	Guiding questions	Response
Transferability (continued)		The experimental testing, FEM and MJBT calculations for CLST could be replicated by other researchers (albeit with different feedstock for physical specimens), as they are conducted in closed experimental conditions.
Sincerity and dependability	Is the research undertaken without undue bias, and is the researcher's personal agenda acknowledged?	<p>The researcher's past experience, positionality and possible biases and assumptions are described in Chapter 3. The research topic was self-initiated and the normative goal of bringing about more reuse in the construction industry is made explicit.</p> <p>Evolution of the systems of end-of-life material management across the construction industry is an incremental process, and the researcher's 'founding' ambition of creating significant change through the EngD was naïve. It has been possible, however, to define a route to potential future change.</p>
Practical significance	Is the knowledge of use? Did methods of data collection arise naturally from the studied context, and was the development of the research shaped by practitioners, based on knowledge of industry practices?	<p>Proposals are developed out of an understanding of the existing context, gained from practice, and the study of practice. The project acknowledges the complexity of the real-world situation and attempts to address the range of mechanisms that appear to create the current scenario. It strives to go beyond suggesting simple tools that might address individual issues, but fail to recognise systemic complexity or the real-world perspective of the practitioner.</p> <p>The contributions to knowledge have both academic and practical value. The triage is integrated with existing practices; its more speculative aspects are explained as outlines and areas that future researchers can fill in with further detail are highlighted. The call for legislative change (submission of E-BAMB information) targets minimum disruption for maximum impact. Without this legislative change, the triage can still be implemented within organisations: the thesis describes a pared down version suited to the context of a housing organisation. This could have been strengthened if the researcher had engaged industrial sponsors' staff in implementing triage activities and stepped back from the facilitating role.</p> <p>Action research is time consuming for participants. The case for their investment of time was not easily made when the goals of the research are intrinsically long-term and global, while contractors' and others' agendas were focused on the immediate needs of projects.</p> <p>Interviews were conducted in the manner of meetings or informal conversations – formats with which participants were more familiar than formal interviews – to create a more natural setting for data collection.</p>
Coherence and commitment	Do the research objectives emerge from the problem statement, and does the study plausibly accomplish its aims through substantial engagement with the subject matter?	<p>The research objectives evolved with the research; after studying the problem to address the first research objective, the nuance of the second and third objectives emerged. Developing out of the initial goal of enabling greater reuse, specific areas for investigation were defined and pursued as more focused and realistic aims for a doctoral research project.</p> <p>These aims were met using methods that were considered appropriate in each given investigation; e.g., to understand existing context in depth, case studies with practitioner engagement were undertaken; to examine the feasibility of CLST, specimens were made and tested. The success of urban proposals that are fundamentally open-ended could not be measured, but the triage is shown from the perspective of CLST to create a context in which reuse ideas are more likely to be able to evolve into real enterprises that achieve social, economic and environmental gains.</p>

7.4.1 Limitations

Limitations of the research associated with each publication have been noted at the relevant points in the thesis and in Appendix N, and have been discussed in Table 28.

Decisions were taken to limit the scope of the research to what was achievable within the confines of doctoral research. The role of specifiers in the uptake of construction products was not examined; the researcher's own experience as an architect stood in place of a wider investigation of architects' and engineers' perspectives on reuse. It was assumed that secondary products must match primary products' performance criteria, price, availability and lead-in times to be adopted by specifiers. It is acknowledged that secondary components may face further resistance in the form of preconceptions of their inferiority. Interviews with contractors and waste management companies addressed the management of unwanted components, or 'supply'; interviews with specifiers could improve the examination of the 'demand' side of reuse.

An overarching limitation that should be acknowledged concerns the challenge of generating evidence to assess proposed changes that cannot be brought about in a research context or isolated in experimental conditions. With awareness of this inherently open-ended aspect of the abductive enquiry, the project has used an action research strategy to anchor theoretical proposals back to the practical reality of construction material management. For instance, live projects were undertaken to test aspects of the triage – the closest it was possible to come to real implementation in the scope of the project. Their limited scale is, however, a poor representation of the industry at large. In the case studies it was possible for the researcher to play an active role in facilitating information and material flows; how well the E-BAMB database functions could fulfil these roles could not be established without introducing a version of the database at scale. The network effect of many users posting and searching the database is critical to its success in matching 'supply' and 'demand' but could not be reproduced in the research.

Even when narrowed to only the application of an information system, the urban-level theories regarding the possibility and nature of component management are too far-reaching to be deductively proven or disproven. The triage is a series of activities that collectively represent a significant evolution of the construction industry's practices; to be effective it requires change on several fronts. Without enacting these changes the potential impacts could not be tested. This potentially unsatisfying outcome was addressed by switching the focus to a single product, and using CLST as a lens through which to question the plausibility of the urban theoretical work, as well as making a contribution to knowledge in its own right.

7.4.2 Improvements to the action research strategy

There was an assumption between the researcher and academic and industrial supervisory teams that the study should aim to improve industrial sponsors' operations where possible. The

researcher defined a research agenda and gained the tacit support of stakeholders within the two organisations at key points during the research process. However, instrumental stakeholders outside of the industrial sponsors – namely, contractors – had not bought in to the project. It was possible to carry out interviews and site visits, and in some cases contractors facilitated reclamation and redistribution of discarded materials from projects, but committed engagement with the research was not viewed as a good investment of time. For a sustained, systematic application of action research methods with the goal of changing construction practices, it is recommended that the terms of engagement with the contractor or other organisation are established at the outset of the research project. A negotiation between long-term global needs and short-term company needs is necessary to ensure that agendas are aligned. In competitive tendering for projects with housing organisations, the envisaged process could be written into tender documents so that the commitment of contractors becomes a contractual obligation rather than a voluntary endorsement.

7.5 Final remarks

Knowledge can take many forms; contributing to the collective research mission is an exciting process. Some researchers' minds will be more attuned to deductive or inductive approaches to generating knowledge, but an abductive approach comes more naturally in this instance. It is hoped that this project opens new avenues that can be taken up by researchers more naturally inclined towards deeper investigation of narrower issues, such as the design and testing of an E-BAMB information system.

The construction industry uses natural resources intensively; in processing natural resources to supply useful materials and components, it is the cause of significant carbon emissions; it creates physical waste; and it creates wastage of the residual performance of existing building components. This wastage is implicit in the way we regenerate cities: demolition, low-value recycling and site redevelopment. It denies future generations the benefit of existing materials, and, in a carbon and resource constrained world, could expose citizens and the industry itself to a future of extremely high construction costs. By showing that reuse, as it is currently conceived and practised, is not the only alternative to dominant waste management processes, this thesis brought a measured optimism to our prospects of delivering improved use of materials. It has proposed and demonstrated strategies that could be implemented now in an attempt to reduce the industry's current impacts and build resilience against future risks.

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Appendices

A. Background of industrial sponsors

Poplar HARCA is a not-for-profit social landlord, founded in 1998. They own and manage a stock of around nine thousand properties that have been legally transferred from the London Borough of Tower Hamlets after tenant groups voted in favour of the change. As well as considerable physical redevelopment work undertaken by the Development and Regeneration Team, there is a strong focus on community regeneration, led by the Accents Team (Arts and Culture, Community, Enterprise, Sustainability). The researcher's time at Poplar HARCA was largely spent in the Development and Regeneration Team's office, and the original industrial supervisor, Chris Johnson, was an architect working in that team. Chris retired during the course of the project and supervision was taken over by Nick Martin from the Accents team.

Tower Hamlets Homes is a not-for-profit Arm's Length Management Organisation, set up by the Council in 2008 to manage twenty-two thousand properties that remain under the legal ownership of the London Borough of Tower Hamlets. Gaining funding for the Decent Homes programme and bringing all properties up to the Government's standard of decency was at the core of the organisation's purpose. The industrial supervisor was Nick Gopaul, a Project Development Officer and CAD Surveyor, and the project was overseen by Will Manning, Director of Asset Management.

If the longer term aims of the project are achieved, Poplar HARCA and Tower Hamlets Homes stand to benefit: financially, through reduced future tender prices resulting from savings that may be made by contractors in disposal and in lessened reliance on new materials and components; environmentally, through prevention of waste from their demolition and soft strip activities and avoided embodied carbon emissions from their construction and refurbishment activities; and socially, through the availability of free or cheap building components that help new enterprises establish themselves and employment in recirculating materials locally towards beneficial reuse within the community.

B. Quantification of Material Stocks in Existing Buildings Using Serendipitous Data – A Case Study for Timber in a London Borough (paper in preparation)

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Abstract

The existing building stock represents a huge accumulation of physical resources: a ‘material bank’ from which future supplies of materials could be drawn to improve resource efficiency. However, in the absence of systematically collected information about materials deposited in these ‘banks’, the ability to manage and exploit them is limited. To address this need, the article proposes a means of quantifying material stocks based on the use of happenstance data about buildings collected for other purposes. The approach is demonstrated by combining data from external research bodies, national statistics and housing stock management databases to estimate the timber stock in residential buildings in the London Borough of Tower Hamlets.

Results show that residential buildings constructed before 1992 (60% of the London Borough of Tower Hamlets’s total housing stock) have a total timber accumulation of around 670,000 tonnes. Assuming 60% of the borough’s population of 305,000 lives in this 60% of housing, the timber quantity can be calculated at 3.7 tonnes per capita. This is within the range of 2.4-4.0 tonnes per capita found in the literature (Höglmeier et al., 2013; Kleemann et al., 2017). Material intensities for timber extrapolated from the data gave results of between 6.8-11.2 kg/m³ for terraced houses and 5.4-11.8 kg/m³ for flats and maisonettes. These totals can be disaggregated to model quantities of different timber building components, allowing, for instance, an assessment of reuse, repurposing and upcycling opportunities for different timber components.

The method and results can contribute to an understanding of ‘existing buildings as material banks’ (E-BAMB) in a number of ways. Researchers can apply the generalised method to other materials in other contexts. Material intensities for different timber components in different building types, established in this paper through bottom-up means, may, with caution, be applied in a top-down manner to other populations of buildings to estimate stocks of timber components. Material intensities can be elaborated and used by clients, design teams, contractors or surveyors to inform pre-redevelopment audits. The data can be used in combination with demolition rates to predict the ongoing quantities of timber likely to emerge from future demolition, allowing proactive planning of waste management as well as

management of components at a higher level of performance and value. A fuller understanding of E-BAMB would allow academics, designers and entrepreneurs to scrutinise the potential for reuse, repurposing, and upcycling processes. This in turn could lead to new markets to which contractors and demolition contractors can divert materials, avoiding or delaying wasteful recycling processes, incineration and landfill.

C. **Paper presented at WASCON 2015 – Resource Efficiency in Construction, Santander, Spain, 11th June 2015**

Mining the construction process and our existing building stock: an assessment of current demolition and waste management practices and a triage process for resource valorisation

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Abstract

The UK construction industry uses 260,000,000 tonnes of raw materials and creates 77,000,000 tonnes of waste a year. The dominant method of managing its waste is open loop recycling, also known as downcycling. Though a step better than disposal to landfill, downcycling involves significant processing and transportation, and fails to capitalise on the value embedded in existing construction components. Reuse can short-circuit these wasteful processes.

This paper presents a background to the current scenario and explains why reuse of construction components has become uncommon. A multiple case study approach is taken, spanning new build and refurbishment in the housing sector. In depth interviews with clients, contractors and waste management companies, and an assessment of the systems of waste management and reporting, reveals a picture of the barriers to reuse faced by the wider UK construction industry. In response a triage process is developed, identifying points at which intervention is needed to bring about change. The key point within the triage is early recognition of an end-user for waste arising. This point is addressed in a proposed intervention, which combines successful elements of previous initiatives in a novel way, creating a mechanism for identifying usefulness and linking available resources to new uses.

Keywords: Reuse; construction; components; waste management; triage.

1 Introduction

The European Commission Waste Framework Directive (2008/98/EC) embeds into law a preferential order of management of waste: after prevention, direct reuse of a product, then recycling (reprocessing into new products), recovery (such as generating energy through incineration), and finally disposal. Efforts to address construction and demolition (C&D) waste have focused on diversion from landfill. A voluntary initiative led by Waste & Resources Action

Plan (WRAP), Halving Waste to Landfill, and the gradual escalation of the Landfill Tax, have been effective (Hobbs, 2011): around the turn of the millennium, 55 percent of all construction, demolition and excavation waste was disposed of by incineration or landfill (Symonds, 1999); today something in the region of ten percent is landfilled in the UK. The main route for these diverted waste streams has been into open-loop recycling processes: downcycling.

The image of recycling, the familiar triangle of arrows, conjures an idea of continuous cycles, yet open-loop recycling is better described as delayed disposal (Anderson, 2011). Where, for instance, timber joists are chipped for chipboard, open-loop recycling still requires trees to be felled, milled and produced when we want new joists, and still requires chipboard to be buried or incinerated, sooner or later. Most concrete from demolition is crushed to make a substitute for primary aggregate. But the aggregate we are now able to replace is around 25 times less energy intensive to produce than the original concrete: to use concrete in this way is downcycling on a massive scale (Allwood et al., 2012). There is a danger of assuming that the impact of construction waste has been successfully mitigated as recycling rates rise above ninety percent. In fact, these processes are highly wasteful of embedded energy.

The aim of this research, therefore, is to understand the mechanisms that lead to material resources in construction and demolition processes being deemed waste, and to identify areas in, and means by which, intervention might enable reuse of construction components. Reuse can short-circuit wasteful recycling processes and address:

- a) environmental impacts of landfill and the costs of disposal;
- b) emissions and social costs associated with production of new construction components;
- c) depletion of natural reserves;
- d) a desire to be resourceful.

2 Methods

The research focuses on housing regeneration in the London Borough of Tower Hamlets as a microcosm of construction in an urban environment in the UK. The industrial sponsors, Poplar HARCA (Housing and Regeneration Community Association) and Tower Hamlets Homes, are constantly carrying out processes of maintenance and regeneration for more than thirty thousand homes. Live projects spanning large and small scale new build and refurbishment have been used as case studies. There are three main sources of evidence: documentation, largely in the form of contractors' site waste management plans and waste reports; long interviews with contractors, waste management companies and members of the two client organisations; and direct observation on site and through visits to waste transfer stations (WTSS).

3 Results

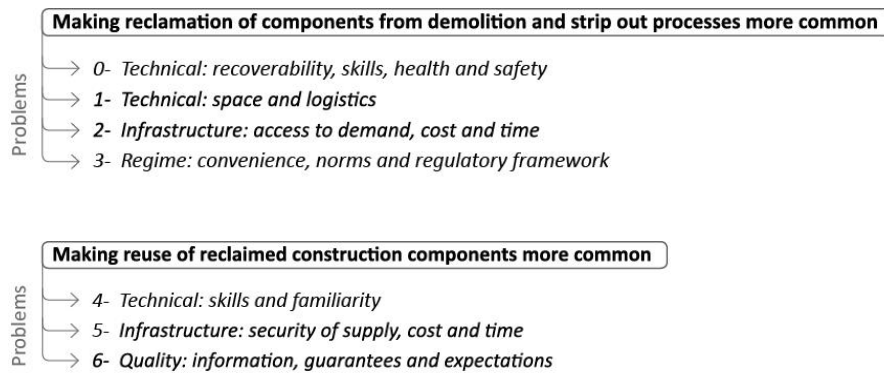
3.1 Waste logistics and reporting

Common to all case study projects except one was a lack of space for separate skips: waste collected by waste management companies is almost always mixed. Therefore, when a skip reaches the WTS, it gets tipped into one big heap and sorted by a series of manual and plant sorting and trommel screening to separate different waste fractions. At this point good materials are too damaged to be reclaimed for the most valuable uses. The WTS carries out primary sorting and logistics, but nothing more: waste is sent on to secondary processors for the next stage, be it recycling, recovery or landfill.

Waste reporting is carried out by waste management companies. They record the waste types and quantities arising from particular projects with varying degrees of accuracy, but do so in a way that is geared towards waste management, rather than best use of resources. Significant differences are evident in reported wastes between projects of a very similar nature, due to inconsistent methods of assessment and inconsistent use of European Waste Catalogue (EWC; EC, 2000) codes.

The reports are useful for checking against benchmarks, improving future forecasting of waste arising, and for planning future waste minimisation efforts. However, the timing of the reporting and the failure to report the qualities of resources means that reusable materials are not identified. The result of these processes of waste transfer and reporting is that recycling becomes the best remaining waste management option, and preference of the higher levels of the waste hierarchy is neglected.

Summing up the existing system of C&D waste management, Figure 1 shows the overall material breakdown for case study projects, and the distances involved in the chains of waste handling and processing. The primary sorting at WTSs is within fifteen miles of the construction sites, and secondary processing generally happens within a fifty mile radius, but beyond that the chains of recycling may be national, European or global, depending on the material. These stages of transportation and processing are carbon intensive, and chipping timber or crushing bricks does not capitalise on the energy embedded in those products. However the existing system is attractive to contractors, because the infrastructure that gathers up materials and underpins recycling and recovery systems is well established. Reuse infrastructure has far fewer hubs and connections, so reusable resources remain scattered, or follow established recycling and recovery routes.

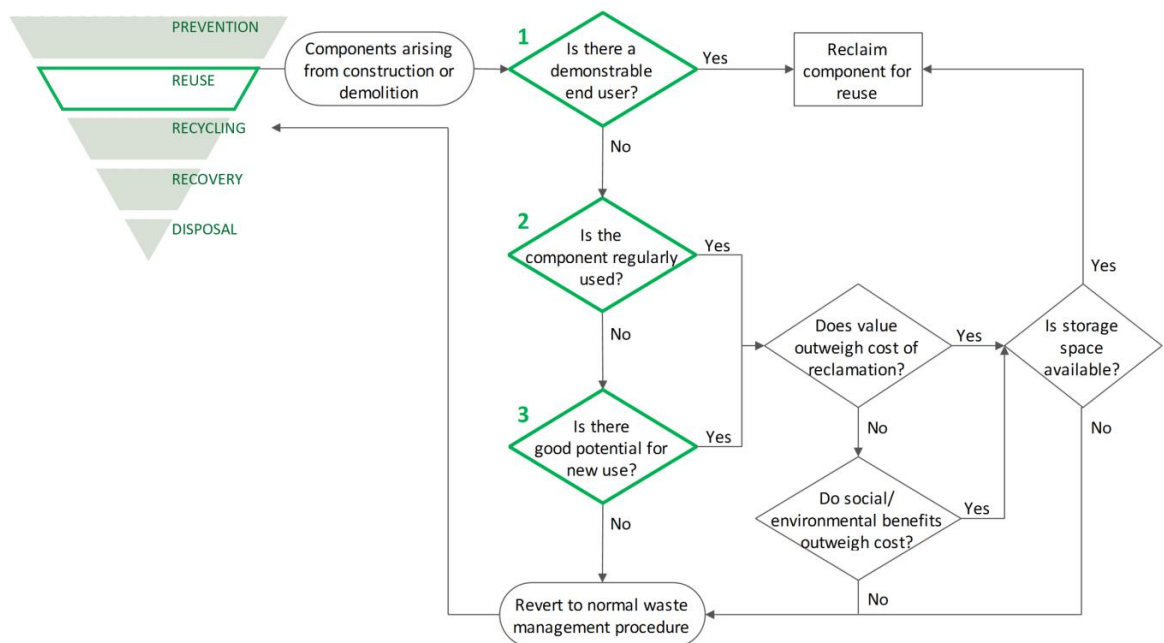


Problem tree categories (Mosard, 1982) relating to reclamation and reuse of construction components

4 Discussion

4.1 Triage process

Based on the research findings, a triage process has been defined (Figure 3). This identifies the points at which intervention is needed to prove usefulness, and thus be able to earmark materials for reclamation. The first question within the triage process calls for a demonstrable end-user prior to discarding a component, as knowing the end-user ensures that the component is useful. We have taken this as our point of intervention.



Flowchart of triage process for separating out components for reuse

4.2 A proposed intervention

Combining elements of previous reuse initiatives, we have developed a proposal that enables components that would otherwise be discarded to be linked to new users. This takes the form of a resource appraisal, which a client intending to carry out demolition would be required to undertake at planning stage – early enough for a new user to be identified – and a resource map, which broadcasts the appraisal findings to a wider community of designers, so as to draw on their collective creativity and knowledge of other clients' needs. Designers would be able to explore this database, include particular components in their proposals, and extract specifications from which contractors can later procure the component.

We have developed a resource appraisal form based on the Common Arrangement of Work Sections (CAWS; CPIC, 1998), a classification system used across the UK construction industry, and tested it on a set of buildings that are soon to be demolished. Using this system treats the materials in a building as resources, instead of as waste, and once the appraisal has been made, the results can easily be matched against new work that is to be carried out elsewhere. In the first instance the end uses are likely to be in smaller projects or community enterprises, but the long-term goal is to be able to supply resources back to the construction industry at large.

4.3 Developing the proposal

There is scope for the intervention to be refined in future, including automation of the appraisal process and integration with building information modelling (BIM). It is expected that BIM will be used increasingly for the management of existing buildings as well as the design of new ones. BIM presents the opportunity to maintain a richer and more useful 'as built' set of information, with the building conceived as a 'materials depot' rather than a liability at its end of life stage. There is an emergent field of study of BIM at neighbourhood-scale (Plume & Mitchell, 2011; Plume, 2013); we envisage the proposed resource map eventually becoming a neighbourhood information model enabling designers to explore all locally available resources.

The results of this work can be built upon to generate greater levels of reuse in the construction industry, with associated environmental, monetary and social benefits. The impact of the proposed intervention could be measured in several ways:

- the quantity of material diverted from landfill;
- emissions and cost savings from waste no longer sent for recycling and energy recovery (gate fees, transportation, processing, new fabrication, etc.);
- emissions savings, cost savings and avoidance of natural resource depletion from new products substituted with reclaimed;
- new jobs created in the local economy.

In a mature state of development, we believe the proposal would go a significant distance towards bringing about our aim of resourcefulness in the construction industry.

5 Conclusions

Summary of main findings:

- Waste leaving all case study sites except one is unsegregated
- Waste is separated at WTSs within fifteen miles of source
- After tipping at the WTS, good materials are too damaged to be reclaimed for the most valuable uses
- WTSs are pivotal to C&D waste management, but are not set up for reclamation
- Reporting of waste is carried out at the WTS: too late in the process for good materials to be identified
- Waste report categories are too generalised to capture material qualities: the EWC codes for different materials are geared towards management of waste not best use of resources
- Methods of waste recording, use of EWC codes, and level of refinement in reports vary considerably between waste management companies
- Secondary processing of waste occurs within fifty miles of Tower Hamlets, but further stages of recycling can be national, European or global
- The infrastructure to support these processes is well established, whilst there is a lack of infrastructure for reuse
- Attitudes and perceived barriers to reuse have been identified through interviews; previous initiatives that have aimed to encourage reuse address some but not all of these barriers
- At the core is a vantage point problem: on the reclamation side, of knowing what is useful; and on the reuse side, of knowing what is available.

The first question in the triage process, to identify the points at which intervention is needed, calls for a demonstrable end-use, and therefore an end-user prior to discarding a component. Intervention could take the form of a resource appraisal, which a client intending to demolish would be required to carry out at planning stage, and a resource map, which broadcasts the appraisal findings to a wider community of designers. We have developed a resource appraisal form based on the CAWS, a classification system used across the industry, and tested it on a set of buildings that are soon to be demolished. We have proposed ways that the intervention could be refined in future, including automation of the appraisal process and integration with emergent neighbourhood-scale BIM.

D. **Paper presented at UCL Urban Sustainability and Resilience *Research Showcase* in London, UK, 10th November 2015**

Viable and scalable reuse in construction: the case of upcycling waste wood to make cross-laminated timber

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Abstract

Timber waste amounts to several million tonnes per year in the UK. The construction industry plays a large part in this waste generation. Much of the waste wood is exported for energy recovery in Belgium, the Netherlands and Sweden. The higher grades of waste wood are usually downcycled into wood panel products, such as chipboard, or even lower value applications like animal bedding. Alongside these environmentally and economically wasteful processes, the construction industry imports vast quantities of new construction products and virgin materials.

Unfortunately, reuse rates have plummeted in recent times. The scope for, and impact of, direct reuse – e.g. reusing a floorboard as a floorboard – is limited. Instead of downcycling or direct reuse, we propose upcycling of low or negative value materials to make higher value, certifiable construction products that match the performance of their virgin resource equivalent.

Cross-laminated timber (CLT) is a structural building material, increasingly used in the UK in lieu of concrete or steel framing, and typically imported from Austria or Germany. We present initial prototypes of a new type of CLT made from waste wood. The results of mechanical testing suggest performance comparable to CLT made from virgin wood. This product innovation represents part of a wider vision of local manufacture, based on the shortcutting of waste export and product import patterns.

E. **Paper presented at EU COST Action, *Mining the European Anthroposphere (MINEA)*, Odense, Denmark, 15th August 2016**

Triage: Designing a Materials Management Framework for secondary use of construction components

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Abstract

Based on findings from case studies looking at the current systems of waste management in construction and demolition projects in London, we have proposed a 'triage' process. This intervention would help in separating out those components that can be reused or upcycled, in order to retain or enhance their value. The triage is a short- to medium- term, project-based approach to materials management, complementing the longer-term building stocks approach (see graphical abstract, attached).

Elements of the proposed process have been tested in a live case study. Two blocks of flats in east London were surveyed photographically for potentially reclaimable components. These were presented to architects working on the fit-out of an office nearby. Ideas were generated for the reuse of various components, and the most promising were designed in detail and costed. Metal meter cabinet doors and timber floorboards were reclaimed: the meter cabinets were reused as the doors of locker units; floorboards were upcycled into cross-laminated timber panels, which have structural capabilities, but were used in this project as a long 'banqueting table'. Both are now in use in the office space.

Although the case study project diverted only a small quantity of materials away from normal waste management, it demonstrated the effectiveness of:

- early identification of forthcoming waste streams,
- designers' creativity in reimagining waste, and
- reuse and upcycling as ways of avoiding loss in value through downcycling.

The process began to instigate a local network of 'grave-to-cradle' infrastructure, but the absence of established reclamation, remaking, remanufacturing and recertifying enterprises is highlighted as a major barrier to adoption of reuse and upcycling in mainstream construction.

F. **Paper presented at *Positions on Circularity in the Built Environment*, Munich, Germany, 14th March 2017**

An urban triage for existing construction components entering the waste stream, and the case of cross-laminated timber upcycled from waste wood

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Abstract

The project stemmed from a perspective of architectural practice in London, and was motivated by the difficulty of specifying reused building components, a goal of greater resourcefulness in construction, and a belief that both the design process and the experience of buildings can be enriched by materials with a past. We set out with the aim of developing systems to enable reuse of waste building components.

The research setting is the London Borough of Tower Hamlets and the project is supported by two social housing organisations, Poplar HARCA and Tower Hamlets Homes. Together they are responsible for the cyclical regeneration of more than 30,000 homes: maintenance, refurbishment, and sometimes wholesale redevelopment of sites. Through their activities and through engagement with their contractors, we have examined the present workings of the construction and demolition waste industry, and begun to test and demonstrate alternative practices. This is the final year of a four year project.

The research has developed on two main levels: interventions in urban (macro-level) systems to create the potential for direct reuse and upcycling of construction components; and a specific (micro-level) product example within such a system. The former is leading to the recommendation of a 'triage' process to separate out those components that can be reused or upcycled, in order that their value be retained or enhanced. This is intended to provide the mechanism by which existing policy measures in support of reuse can be implemented in practice.

Take-up of direct reuse in mainstream construction is nevertheless expected to remain limited unless there is certainty over quantities and qualities of goods. In the future, increased resource prices may create a situation in which consolidation and recertification of certain waste streams for reuse is viable. In the meantime, there appears to be a need for transformational processes that enhance the value of waste materials. Value added through upcycling creates

the business case for gathering waste, processing and supplying products to a demanding industry.

In this project and in a future research proposal we intend to examine how this concept of upcycling can be defined. How does it differ from recycling and downcycling? We do so through the case of cross-laminated timber made from waste wood: a previously untested application of waste wood to an increasingly common structural component. This example product allows us to demonstrate the potential environmental and social benefits of local upcycling in comparison to reuse and typical recycling, and to investigate technical and economic viability.

G. Method for literature collection and analysis

The application Mendeley was used to develop a structured library of folders, in which publications could be associated with more than one folder. As the collection of literature grew, the emergent themes were given folders or sub-folders. The library structure is reproduced in Figure 42. Literature was selected by maintaining a series of Google Scholar alerts that were adapted over the course of the project to produce more related results (Figure 41), and Mendeley suggestions, providing more focus based on articles with similarities to items already saved in my Mendeley library. Together these produced around 100 results a week. These were assessed for relevance by reading the title, then if relevant, the abstract or executive summary. A decision would be made at that point about whether to save the document, and if so, whether to read further immediately. Brief notes were made on the abstract and parts of paper skimmed or read, and on the extent of reading completed. The library consisted of around 1,500 publications considered of relevance to the research. Where literature connected closely to thinking and findings developed elsewhere in the project, forays were made into those subjects by reading articles in full, using Mendeley's notes and highlights functions, and following up sequences of citations. As the EngD is finite, while there is no natural break between the topic and ever broader spheres of knowledge, an artificial boundary has to be drawn around the review of literature. Likewise, the EngD's limits mean that a line also has to be drawn below the process, while the body of literature on the topic continues to grow rapidly. Google Scholar alerts and Mendeley suggestions after September 2017 were not reviewed comprehensively.

upcycling timber wood construction waste - new results	Show up to 20 results
"waste hierarchy" construction reuse materials -sludge -pulverised - new results	Show up to 20 results
triage construction waste material -vaccine -vitro -pulmonary - new results	Show up to 20 results
reuse construction waste materials -"cement replacement" -"recycled coarse aggregates" -leaching - new results	Show up to 20 results
pre-demolition audit reuse construction - new results	Show up to 20 results
remanufacturing construction materials waste -"us patent" -thermochemical -polymers - new results	Show up to 20 results
"circular economy" construction waste materials -sludge -pulverised -"blast furnace" - new results	Show up to 20 results

Figure 41: Google Scholar alert search terms at the end of the project

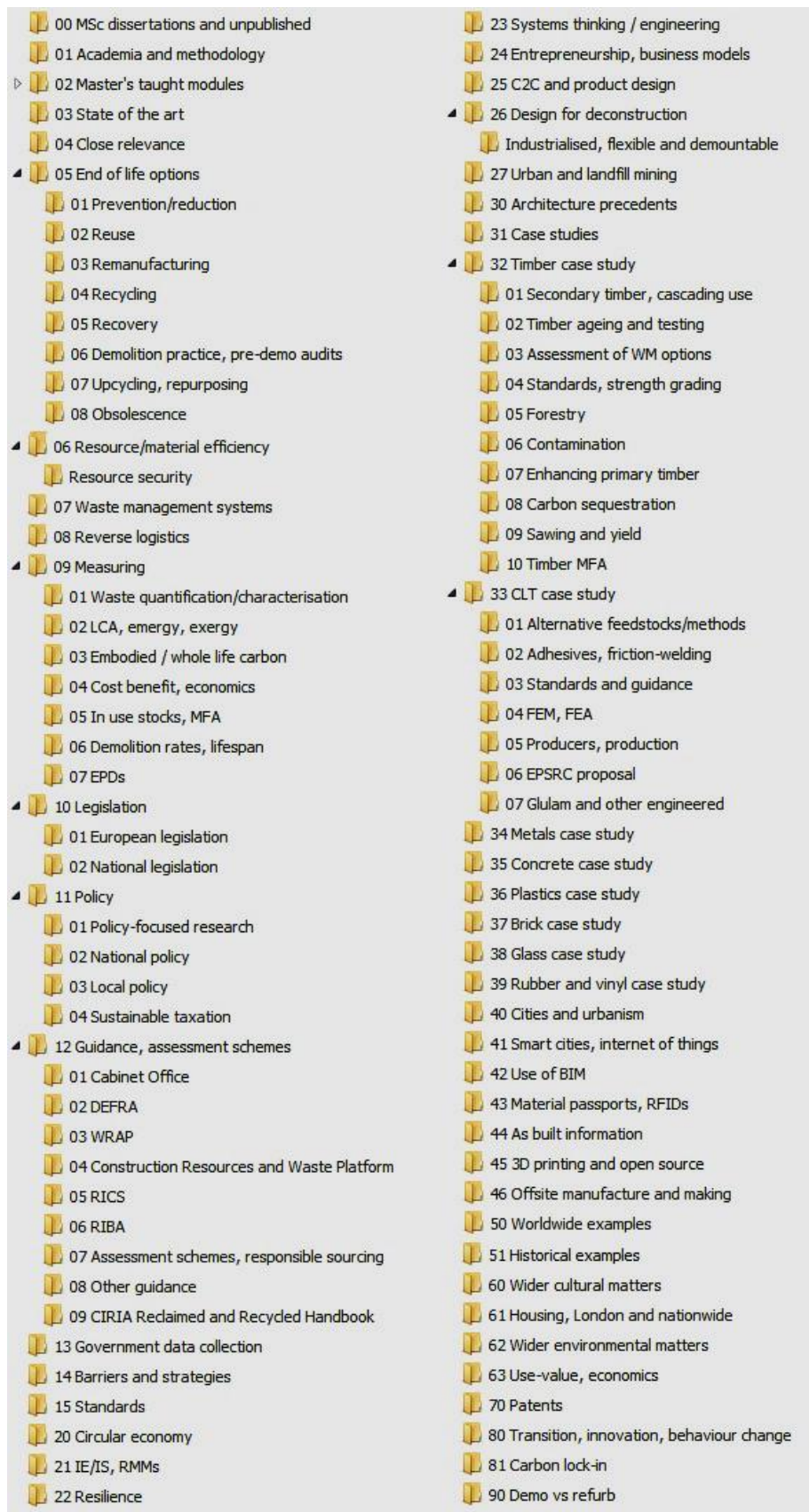


Figure 42: Mendeley library folder structure

H. List of invited industry, policy and academic workshops and seminar discussion groups attended

In addition to public lectures and events, the following invited events contributed to the gathering of data related to the research topic:

EU LIFE Bid: Closing the loop in the building sector, Useful Simple Projects, 21st July 2014, at the RSA, London. One-day project planning workshop.

London Infrastructure Plan 2050: Circular Economy, GLA, 27th November 2014, at City Hall, London. World café style half-day workshop.

Deconstructing Demolition: Scrap and Salvage, UCL Art Museum on Tour, 27th November 2014, London. Tour of demolition sites led by UCL artist in residence, Hilary Powell.

CE100 Acceleration Workshop, Ellen MacArthur Foundation, 6th-8th October 2015, Milan. Meeting of members of the Circular Economy 100 with presentations and workshops.

Timber in a Circular Economy, UCL CircEL, 20th July 2016, at UCL, London. Workshop on the future of timber and furniture in a circular economy.

Reusable Buildings Network, ASBP, 29th September 2016, at ASBP, London. Workshop to share latest research and projects.

London Carbon Innovation Challenge, London Waste and Recycling Board (LWARB) and Climate-KIC, 6th December 2016, London. One-day event developing business plans with industry experts and pitching for a prize of £20,000. CLST reached final and was pitched to Dragon's Den-style panel by the researcher.

The Loop – Bringing the benefits of reuse to estates, Groundwork, 17th January 2017, at Groundwork Loop Grahame Park, Colindale, London. Visit to reuse and upcycling enterprise.

Typology of Construction Components for Reuse, ASBP and the University of Leeds, 4th April 2017, at ASBP, London. Focus group examination of Leeds researchers' proposed 'typology'.

Material Passports and Buildings As Material Banks: KTP Steering Committee, University of Cambridge, 19th July 2017, at BAM Construct Ltd, London.

Developing with CLT in London and the UK, UCL Centre for Urban Sustainability and Resilience, 25th August 2017, at UCL, London. Workshop to discuss cross-laminated timber with visitors from Nelson Mandela Metropolitan University, Port Elizabeth, South Africa.

CLT Hackney walking tour, ASBP and Waugh Thistleton Architects, 27th September 2017, London. Discussion of Hackney 'wood first' initiative and visits to CLT buildings.

Resource Efficiency in Construction and the Built Environment – 1, University of Cambridge, 10th January 2018, at ASBP, London. First meeting of group to create forum for sharing latest projects and research.

Resource Efficiency in Construction and the Built Environment – 2, University of Cambridge, 24th September 2018, at Grimshaw Architects, London. Second meeting of group with presentation by author.

I. Master's collaborators' dissertation abstracts

1. Cross-Laminated Timber from Waste Wood and Comparative Life Cycle Assessment

Evi Unubreme, September 2015

Timber consumption has been on the rise in the UK in recent years with up to 10 million tonnes consumed in 2010 (WRAP, 2011). Due to the consumption of vast quantity of timber annually, there are large quantities of timber waste generated from the different streams.

The timber waste generated varies in quantity and grade and is currently been burnt for biofuel; recycled to make animal beddings and furniture; or disposed of by Landfill which incurs additional cost for contractors and the methane gas emitted is harmful to the environment. An alternative use of this timber waste is the production of Cross laminated Timber (CLT). CLT is an engineered timber product which is a suitable component of structural element like shear walls and roof assembly. For it to be used as a structural material, the mechanical properties were tested and compared to new wood CLT produced under the same conditions in the laboratory.

A relatively good performance though not equal to that of the new wood CLT was found. The comparative Life Cycle Assessment (LCA) showed positive effect on some of the GHG emissions when waste wood is used in place of virgin timber. Further testing needs to be performed with the waste wood CLT limiting factors mentioned in the study improved on.

2. Cross-Laminated Timber from Waste Wood and Assessment of Barriers

Tianyao Lyu, September 2015

Cross Laminated Timber (CLT) has become a popular material nowadays. From the structural members to the whole building, it can be modified to various sizes in order to be used in the construction. Except the advantages in the energy conservation, it also performs well in the mechanical property. A series of experiments have been done in exploring the mechanical behaviour. However, there are no such experiments applied to the CLT made from waste wood. For more environmental protection, it is needed to test CLT from waste wood by the same methods.

The aim of this project is to make CLT from waste wood as well as new wood based on the making procedure in factory, and then compare them by testing their mechanical behaviours. Bending test, shearing test, compression test, tension test and moisture content test will be applied on them based on British standards and Eurocode. The results will be analysed by T-test to give a more reliable comparison between the new wood and waste wood. In addition, the

barriers which could happen during the massive production of CLT from waste wood will be analysed.

The results show that the waste wood has some of the same strength to the new wood according to T-test. However, there are still some differences between those two categories due to some limitations and impact factors. The barriers which have been researched include the markets, competing material/product, financial factor and some technical problems in sorting and grading. The dissertation shows that the waste wood has the possibility to be used in production of CLT under the proper handling of waste wood and improvements in the barriers.

3. Reuse: Opportunities for better use of waste construction materials – An Investigation on public attitudes using a video and a survey

Yushi Li, September 2015

This study focuses on C&D waste management in the UK, including the problem and reuse of C&D waste, as well as the digitalisation of its waste management systems. The implementation of this project includes two main parts: video production (Figure 43) and questionnaire surveys. The content of the video is mainly based on the project conducted by Rose (2014). The questionnaire surveys include a pre-video questionnaire and a post-video questionnaire, which were designed to investigate people's understanding of construction waste reuse before and after watching the video, respectively.

The main target audience of this project was contractors, designers and architects, as they are the primary decision makers of the supply end and the demand end of reclaimed materials, respectively. In addition, the general public is also a part of the target audience, since the proposed information system is open to anyone who wants to sell or buy reclaimed materials. For example, discarded timber joints can be used not only for another construction project, but also for someone's garden shed. The video significantly improved people's understanding of construction waste problems, reuse and recycling. Questionnaire results indicated that the market demand for construction waste reuse is considerable. Most respondents found the proposed reused material information system useful.



Figure 43: Video stills from *Reuse: Opportunities for better use of waste construction materials* on YouTube, www.youtube.com/watch?v=r0Ejq_4GXEA

4. Processing and Removal of Contaminants in Cross-Laminated Timber (CLT) Production from Waste Wood

Crystalbale Tiu, September 2016

Large quantity of waste wood generated in the UK is downcycled into lower value products. In other words, 70% of the solid waste wood that can be re-used, has not been put to good use. By implementing the hierarchy waste management policy and cascading use of wood, waste wood that are mostly in their solid form, should be reused and produced into higher value product. Since the crosswise orientation of CLT allows mutual correction of imperfections, it provides an opportunity to utilise imperfect waste wood as its base material. However, this idea required an environmental permit from Environment Agency, as it involves the use and disposal of waste.

The aim of this research was to propose a process to manufacture CLT from waste wood. Understanding the impact of contaminants in waste wood is essential, however, only addressing the process of removing contaminants in waste wood is not enough to justify the feasibility of waste wood as CLT base material. Strength grade of waste wood is important as well, and has to be taken into consideration while choosing waste wood for CLT. By gathering information available from literatures, British Standards, and search engines, requirement of CLT base material, types of contaminants, methods to identify and remove contaminants as well as the cost estimation of waste wood CLT are found.

5. Finite Element Modelling Of Cross-Laminated Timber from Waste Wood

Thibault Dufresne, September 2017

Timber constitutes a significant proportion of construction and demolition waste. Though some of it arises as pieces of useful size, most waste timber is chipped for conversion into lower value composites, or energy, i.e., downcycled. This project is part of a larger study that evaluates the possibility of upcycling waste wood to produce Cross-Laminated Timber (CLT). Waste wood CLT has been manufactured and tested in preliminary laboratory tests at UCL and its properties appeared to be somewhat different to those of CLT produced using new wood. This project uses finite element modelling to better understand how the properties of CLT from waste wood differ from those of CLT from new wood. Several compositions of CLT created with different types of timber were tested with the finite element software ABAQUS as well as CLT with handmade defects that can be found in waste wood and natural defects that can be found in both new wood and waste wood. It was found that the elastic properties of CLT were hardly damaged by small holes like nail or screw holes usually found in waste wood. However, bigger defects like notches were found more damaging and increased the risk of failure. A key issue in the production of CLT with waste wood as base material CLT are the uncertainties about the species and properties of wood found in the waste wood mix. Further research on assessing the properties of waste wood could be carried out.

6. Life Cycle Assessment (LCA) of Cross-Laminated Secondary Timber

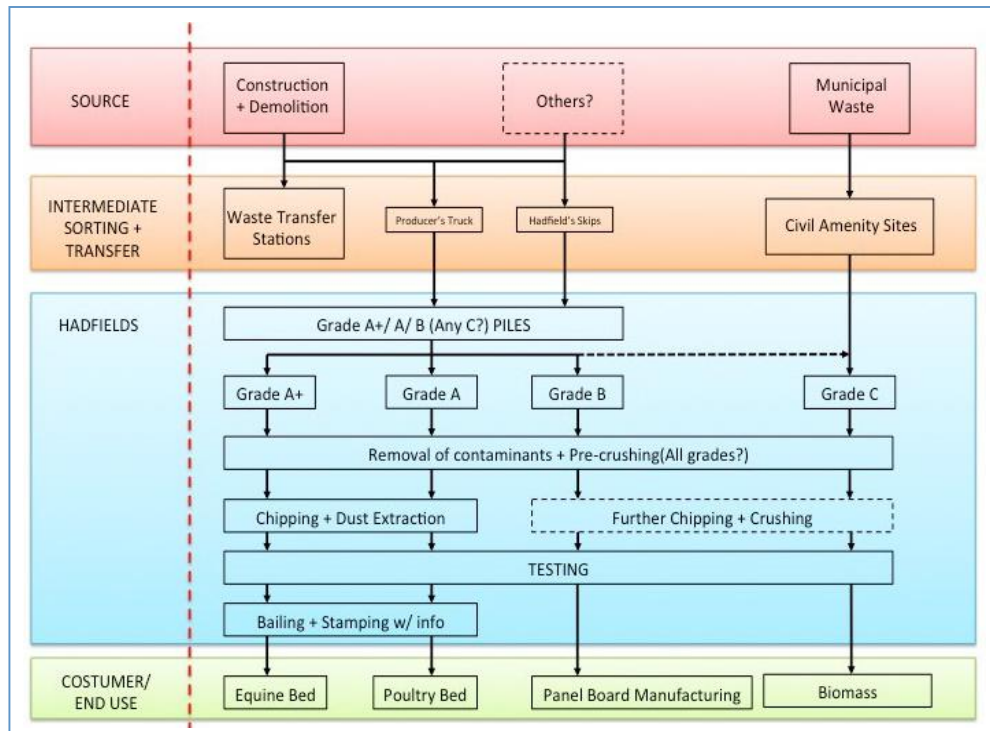
Xing Zou, September 2017

Cross-laminated timber (CLT) has gained increasing popularity as a versatile construction material all over the world. As more attention is paid to recycling waste to substitute raw primary materials, waste wood is a potential source of material to produce CLT. However, waste wood recycling involves various kinds of decontamination and this process may result in extra environmental impact. It is important to determine whether or not CLT production from waste wood has less environmental impact than CLT production from new wood, to be able to provide recommendations for relevant associations and CLT manufacturers. This study quantified and compared the environmental impact between the two processes of CLT production, i.e., from waste wood, or from the new wood, using the life cycle assessment (LCA) method. The ReCiPe2008 was used as the method of life cycle impact assessment in the LCA. The result showed that CLT production from waste wood made less contribution to environment than the CLT production from new wood. Among the impact categories assessed in this study, global warming potential to human health was the most significant contributor in the processes of waste wood CLT and new wood CLT. Additionally, some suggestions were provided to reduce the environmental impact based on the LCA results. See Appendix U for further interpretation.

J. Field notes from visits to secondary timber management sites and CLT factory

Records of findings from site visits 1 and 2 drawn from Romero (2017).

1. Hadfield Wood Recyclers, Manchester, 22nd June 2016: Colin Rose, Alejandro Romero, Crystalbale Tiu and Julia Stegemann.



Grade A+ Wood: Mainly consists of good condition solid timber (i.e. Cable reels). Primarily used for animal bedding



Animal bedding: From Class A recycled timber, primarily used for poultry

2. Community Wood Recycling Project (CWRP), Brighton, 23rd February 2017: Colin Rose and Alejandro Romero.

Introduction to CWRP

The Community Wood Recycling Project is a National Network of over 30 individual local businesses across the UK doing wood collection, preparing for reuse, resale; with some of them doing further product manufacture and some others sorting out the saleable material, de-nailing and selling. CWRP effectively acts as an 'umbrella organisation' (rather than strict franchise model); with headquarters in Brighton. Each project is its own business, run by its own management team. They pay a small franchise fee for the expertise, start-up manuals and support from HQ.

Facts and data collected

- 30 individual 'projects' (project = local business doing wood collection, preparing for reuse, resale; some projects do more product manufacture, some simply sort out the saleable material, de-nail and sell). They have established that to be feasible, a project needs to cover an area that is home to approx. 800,000 people – for there to be enough construction work going on. This means that they won't allow new project to start if they are in an area already covered by an existing project.
- Of around 50 applications to start new projects, about one is successful.

- Centralised sales and marketing based in Brighton – where management of relationships with major national contractors takes place – when they get enquiries for wood collections from construction sites the sales HQ passes on the contact to appropriate local project. 10% of wood collection income from these contracts goes to HQ, the rest to the project in question.
- Pre-Qualification Questionnaires to get involved with national contractors in the first place
- Use Customer Relationship Management software – i.e. run as efficient, proper business.
- Different projects take different positions – some are purists about not using any new wood – in Brighton they will sometimes buy new scaffold boards, as well as dealing in non-timber products – light fittings etc. – other revenue that helps to make a more comprehensive offer, for instance to customers looking to fit out a shop. Customers are typically householders, small business owners (particularly cafes buying furniture), and small builders – but not major contractors.
- Currently 30% 'grade 3' sent for chipping – varies from project to project and from time to time.
- Reducing the percentage of material that goes for chipping is key. Previously they have carried out research into using grade 3 wood as feedstock for making pellets for biomass boilers, or briquettes and logs. The numbers didn't stack up so they're still looking for new ideas for how to make better use of these materials.
- Sales and marketing HQ – sort out formal invoicing and credit control for relationships with national contractors. Making these relationships work is crucial – it's rarely enough to speak only with someone at the top of management, they need to address people in health and safety, sustainability and at site level as well. They have a number of long term working relationships including with Willmott Dixon, Wates and BAM.
- Turnover in Brighton project is more than GBP 400,000. Nationally it is over GBP 1m.
- Householders cannot bring materials directly to the site, as it's not a licensed waste transfer station. They are licensed waste carriers; after the waste wood comes in, it is through the sorting process that it is no longer deemed 'waste'. This is all openly agreed with the Environment Agency – although details were somewhat fuzzy.
- Scaffolding companies do use boards repeatedly, chopping them down to shorter lengths when the ends are damaged – so ultimately they have a waste stream of short lengths (3 ft) in the corner of the yard. CWRP tend to get a call when there is so much of this that they need it gone – but by this stage it tends to be very rotten from being kept outside.

Addressable market

CWRP collect timber from construction sites, which would otherwise have a separate 8-yard skip for timber. They are competitive in terms of pricing; they cannot compete with the cost of 40-yard skips. Waste wood is also sometimes collected from schools and universities, ex-stock from builders merchants, and sometimes directly from furniture manufacturers and scaffolding companies.

Operations

Collection

- Instead of putting waste wood in a skip, contractor puts it in an enclosure formed by three HERAS fences – an area equal to that of an 8-yard skip, and uncovered. When it is full the project collects the timber, loading it into a 3.5 tonne cage truck by hand. This means the wood is kept in good condition, avoiding the practice of using a machine to crush wood to make more fit in the shape of a skip.

Sorting

- Back at the yard, the wood is unloaded by hand and sorted into lengths, pallets and sheet materials (Figures 1 and 2). CWRP have their own 40 yard skip for 'grade 3' - wood that cannot be reused – because it has too many nails, too badly damaged, delaminated, rotten (also MDF/chipboard/OSB in unhelpful sizes/shapes?). This goes for chipping when full.

Processing

- Pallets are broken down using a pallet breaker and de-nailing gun.
- Other materials are de-nailed.
- Materials that can be sold as is go straight to shop (Figure 3). Those that are more useful as feedstock for product manufacture are taken to workshop – preferably on same site but in Brighton, two different sites.
- Workshop (Figure 4): largely using pallet wood, scaffolding boards and joists to make furniture. They also make bird boxes, planters, and other items as requested by customers, such as cladding.
- The processing tasks are an important part of their operations because they are low skilled jobs that people who have, for instance, been long- term unemployed can start to do, gain confidence, put on CV, and get back into employment.
- Volunteering opportunities provide a third revenue stream, alongside waste management service and material/product sales.



Figure 1: Unloading of 3.5 tonne cage truck by hand



Figure 2: Secondary timber sorted by lengths



Figure 3: The Wood Store, CWRP's shop floor



Figure 4: Workshop, used largely to make furniture

3. Stora Enso CLT factory, Ybbs an der Donau, Austria, 14th June 2017: Colin Rose and Julia Stegemann, with Thomas Demschnr, Stora Enso Research and Development manager.

Introduction to Stora Enso (SE)

- Wood products make up 15% of all SE production. Many wood products besides CLT. SE produce 140,000 m³ CLT a year (compared to 5,600,000 m³ of sawn timber).
- CLT production by KLH, Binderholz, Mayr-Melnhof Kaufmann, SE, and somewhat smaller Hassler makes up 60% of total world production.
- 1m³ of timber grows in Austria every second, so could build a family house in 40 secs.
- TU Graz and KLH did a lot of the early technical development.
- SE produce glulam in standard sizes 105x105 and 120x120, in 4 and 6m lengths. Whereas all CLT is produced to order.

CLT technical

- Pine and spruce in almost all CLT, but only spruce on visible surface.
- At least 4:1 width: thickness less important when edge gluing, less likely to have rolling shear.
- Use only C24, as all Austrian manufacturers. But many knots visible - he says not a problem, as the crosswise lay-up means risk is aggregated out. Does this mean they're not genuinely C24 grade but everyone knows it is fine?
- New wood can be steamed to rehydrate as well as kiln dried to reduce moisture content.
- SE unusual in doing edge gluing - mostly for visual reasons, to avoid large visible gaps between boards. Glue is non-structural standard. Can be chaotic when individual boards are laid up in hydraulic press; some factories do not even finger joint end-to-end.
- Single family house comes on one trailer and is erected from raft foundation / slab in one day.
- Timber beam to timber beam connection - adequate with just two fully threaded screws, no plate and bolts - in fact this weakens the timber by making large holes.
- Spread of flame - they achieve Euroclass D s2 d2 - don't need to apply varnishes etc..
- Classified for use in Service Class 1 and 2, but not 3 - though it would likely cope in the most onerous weather conditions in practice.
- Brettstapel and other adhesive-free products - much weaker, too much risk of slippage. For walls, maybe, but not floors.

Testing

- Test REIM: fire resistance (continues to carry load), fire integrity (continues to provide separation), fire insulation (continues to resist transfer of heat), mechanical (ability to cope with mechanical impact in typical fire).
- Delamination test involves full submersion, put in vacuum, submersion, vacuum, several times - check no fail in glue line, only in timber
- Pull out strength test - much weakened if not edge-glued and you hit a joint.

Modelling performance

- Thermal inertia - his own calculations - CLT comes out in the region of masonry for avoidance of overheating, far better than timber frame, slightly less good than concrete.
- SE software for testing design - Calculatis - including insulating properties, dew point calculations etc. - checks for problems and suggests solutions to any it identifies.
- Use shear analogy and FEM. Deflection is usually the design governing factor.

Process

- Before enters the CLT mill - forestry, sawn, kiln dry to 12% (usually - down to 9% minimum? if visual is critical to minimise chance of visible splits), strength grading.
- X-ray scan to check moisture content and density, rejects anything too light.
- Chop off imperfect ends, plane all round.
- Finger joint into endless length with fast-drying PU adhesive.
- Apply emulsion polymer isocyanate (EPI) 2-part non-structural adhesive to one edge, chop into consistent lengths, edge joint into single lamella panel, apply sideways pressure.
- Cut panel for crosswise lamellae, lift them and set down to one side. For lay-up, base lamella has PU adhesive with longer open time applied from one end to the other; mechanised rig with vacuum suction pads brings in crosswise lamella from the left, lays it perfectly in position, moves off to right, picks up next crosswise lamella; meanwhile adhesive applicator passes back over panel; second rig drops longitudinal lamella directly down from above; adhesive applied; first rig brings in lamella from right - and so on.
- Conveyed into hydraulic press, pressed for double the open time. Can do lay-up and pressing of two panels in one go; same process but simply missing out one adhesive application. Complete panels lifted by rig using hoop belts.
- Trim to size; make cut-outs as required; finish by sanding all round.

K. Survey of Poplar Riverside Housing Zone ‘existing buildings as material banks’

In collaboration with Alejandro Romero, a survey was undertaken of the buildings slated for demolition as part of the Poplar Riverside Housing Zone (PRHZ). This is one of about thirty zones in London designated as having high potential for growth, and receiving GLA funding to accelerate housing development. PRHZ contains ten individual sites of regeneration that are intended to produce almost 4,000 new dwellings (GLA, 2018b).

The survey involved the analysis of satellite photography to establish building footprints, storey heights and to identify building and construction types; calculation of building volumes; allocation of each building to the most similar class in Kleemann et al. (2016); and application of Kleeman and colleagues’ material composition factors to calculate mass of each material in each building class on each site.

The results are represented in Figure 44 and Figure 45, and were presented to a member of the PRHZ team at the London Borough of Tower Hamlets. Proposals from the main research project were tabled in a discussion of the potential to reduce waste from the forthcoming demolition and enable local reuse. A guidance note and a paragraph to be entered in tender documents for each site were provided but the Council appear not to have acted upon this work.

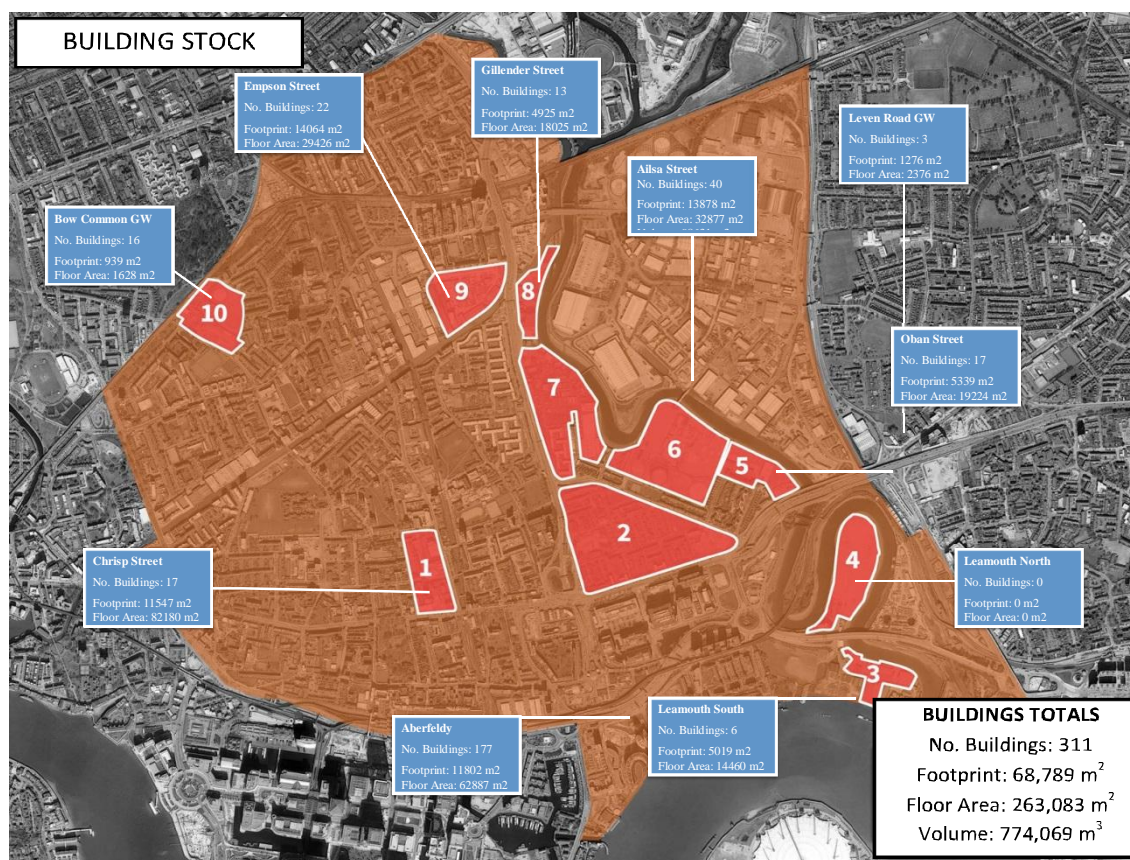


Figure 44: Map of PRHZ sites with overlay of building stock calculations

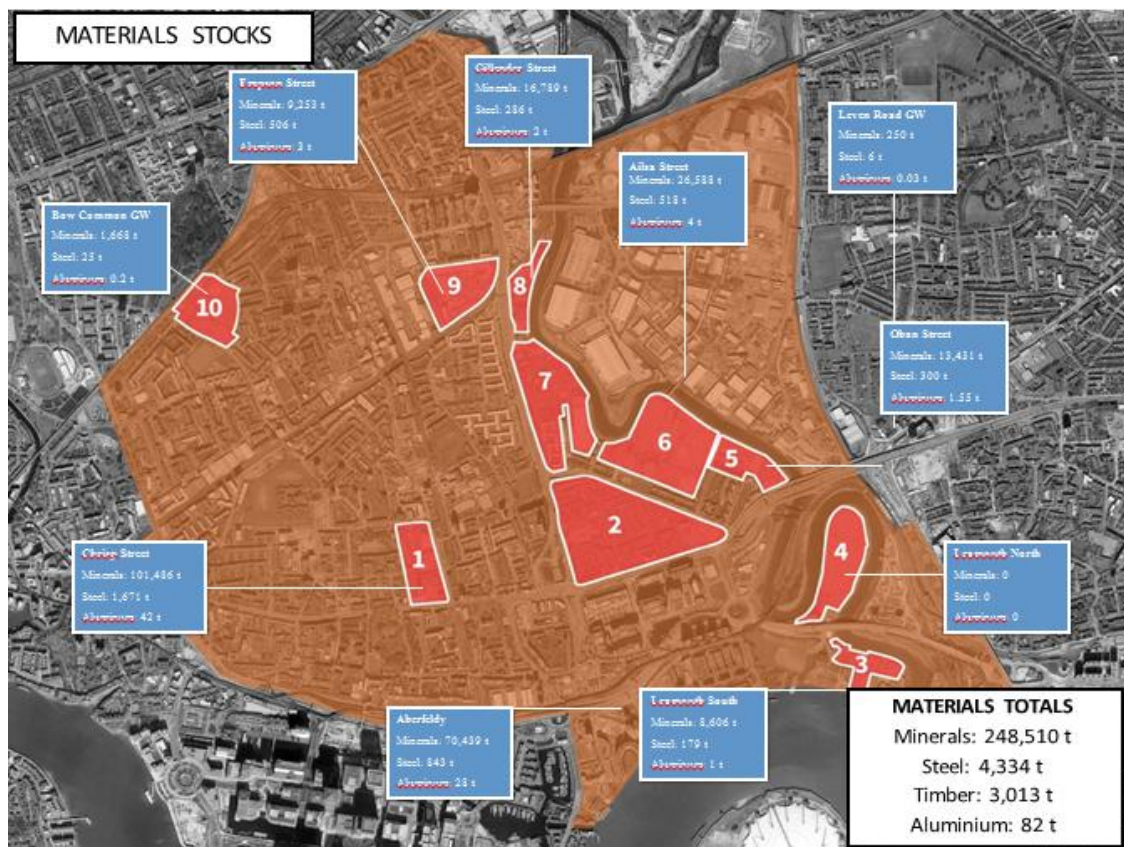


Figure 45: Map of PRHZ sites with overlay of material stocks calculations

- L. Posters presented at the Victoria & Albert Museum *Friday Late*, London, 29th July 2016



Construction materials for a circular economy

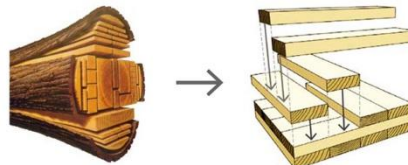
Cross-laminated timber (CLT) is a structural material made by gluing together pieces of wood.

A movement is growing towards the use of CLT and other timber products as the main structure of buildings, in place of carbon intensive concrete and steel.

This ten-storey building on Dalston Lane is an example - but all 3,000m³ of CLT panels are being shipped from Austria!

UK plc pays, in both cash and carbon, to export its timber waste, then pays again to import construction materials like CLT.

Can we come up with ways to add value to the materials we discard, and shortcut these wasteful processes? Here we look at one example: manufacturing CLT locally, using London's waste wood.



CLT: structural panels made from layers of solid wood



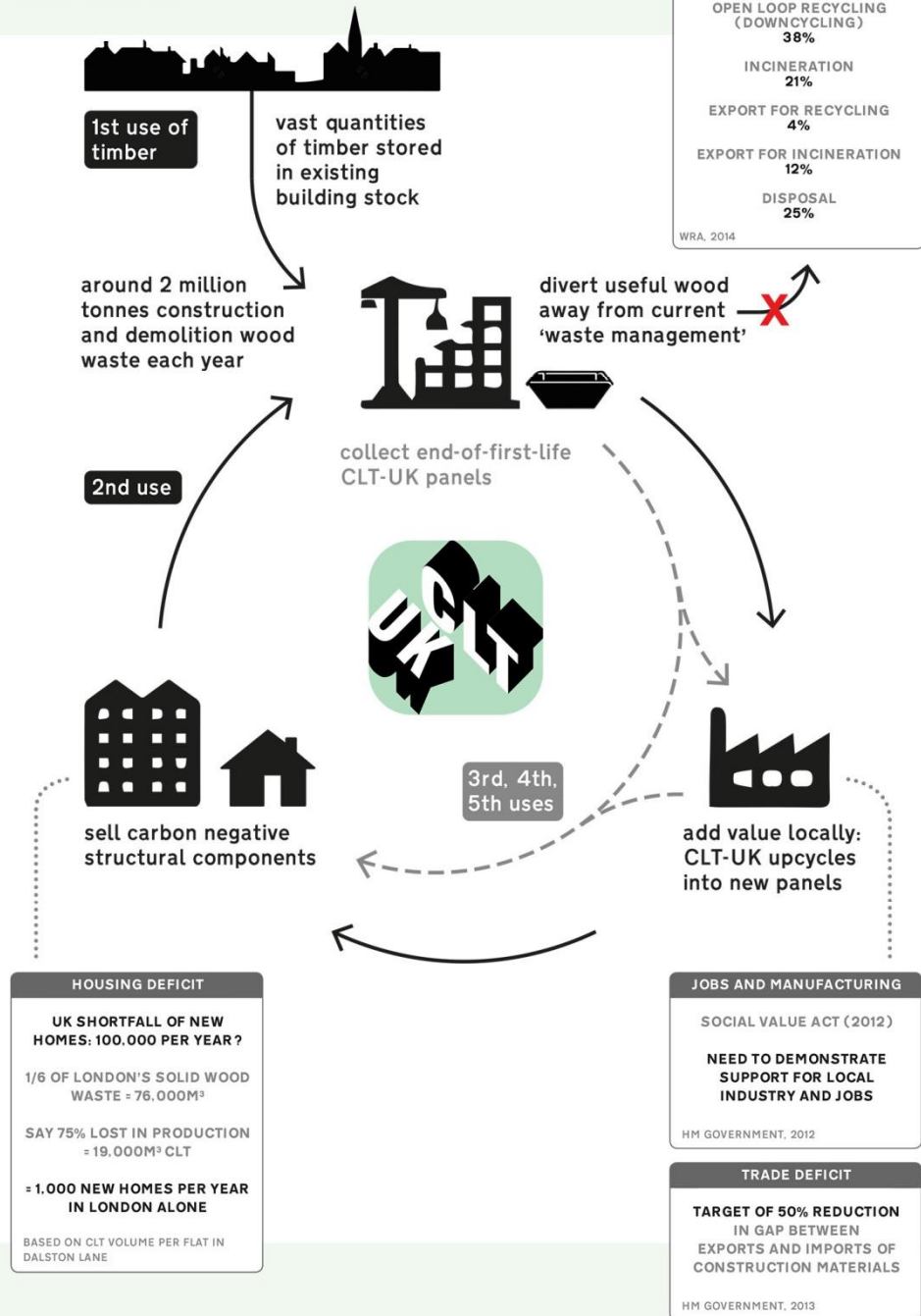
CLT going up now: Dalston Lane by Waugh Thistleton Architects



At present, CLT comes into the UK from abroad, and timber waste goes out: both trades are increasingly expensive

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Schematic for an enterprise making reusable CLT panels from construction and demolition wood waste



Pilot project: Chrisp Street Exchange

In partnership with Poplar HARCA, we tested the CLT from waste wood process by reclaiming timber floorboards from a building that is due to be redeveloped, and transforming them into CLT panels.

The panels are now in use as a banqueting table designed by Seán & Stephen Architects, in a new co-working

space in Poplar. Samples from the project are on display in this exhibition.

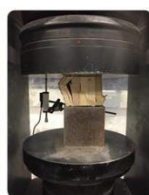
We have carried out initial structural testing in the labs at UCL. We plan to continue research on the idea's technical and financial viability, exploring options of how to operate UK-CLT as a business.



World's first CLT made from waste wood?



Pilot project instigated a local reuse network as well as testing the CLT making process



CLT samples constructed from new and waste wood: destructive testing in UCL labs to examine failure modes

M. Background of the case study projects in Rose and Stegemann (2018a)

Table 29 and the paragraphs that follow give a broad overview of the construction and refurbishment projects used as case studies in the study's initial phase, to provide additional context to the research. Figure 46 locates the sites in a map of the London Borough of Tower Hamlets.

Table 29: Key project information for case study projects in Rose and Stegemann (2018a)

Project	Form of contract	Dates	No. units
Aberfeldy Village whole estate	JCT Design and Build	Project inception: 2010 Expected completion: 2022	1,200
Aberfeldy Village Phase 1a	JCT Design and Build	Mar 2013-Dec 2014	Included above
Aberfeldy Village Phase 1b	JCT Design and Build	Jul 2013-Aug 2015	Included above
Aberfeldy Village Phase 2	JCT Design and Build	Start Sep 2014 tbc	Included above
Knapp Road	JCT Design and Build	Project inception: Sep 2009 Construction: Jan 2013-Aug 2014	35
Decent Homes whole programme	NEC partnering agreements	Apr 2011-Mar 2016	Internals: 10,663 Externals: 10,961
Decent Homes Lot A	NEC partnering agreement	Apr 2013-Mar 2016	Internals: 2,248 Externals: 4,110
Decent Homes Lot B	NEC partnering agreement	Apr 2013-Mar 2016	Internals: 2,442 Externals: 3,586
Decent Homes Lot C	NEC partnering agreement	Apr 2013-Mar 2016	Internals: 1,889 Externals: 3,265
Decent Homes Lot X	NEC partnering agreement	Apr 2013-Mar 2016	Internals: 597
Decent Homes Lot Y	NEC partnering agreement	Apr 2013-Mar 2016	Internals: 593
Responsive maintenance	Service contract – price per property	Ongoing	Approx. 22,000

Aberfeldy Village and Knapp Road

The two Poplar HARCA case study projects fall into the new build category. Aberfeldy Village is a phased development involving the gradual demolition of more than a dozen mid-twentieth century buildings and regeneration of the estate, over the course of almost ten years; Knapp Road is a single building on a constrained site, with demolition of the existing building and new construction due to last about a year. Both are being undertaken by major housebuilders.

The phasing of the construction at Aberfeldy Village means that the site compound layout will change over the course of the project. Although the site for each phase of the development is large, the boundaries are constrained by existing neighbouring properties, which remain largely

occupied. The main contractor employs little direct labour; their role is to manage a great number of subcontractors. The primary issue at Knapp Road is a severely constrained site. The site boundary is only marginally bigger than the footprint of the new building. Additional space for the site compound is not available due to the close proximity of neighbouring properties and a playground to the north.

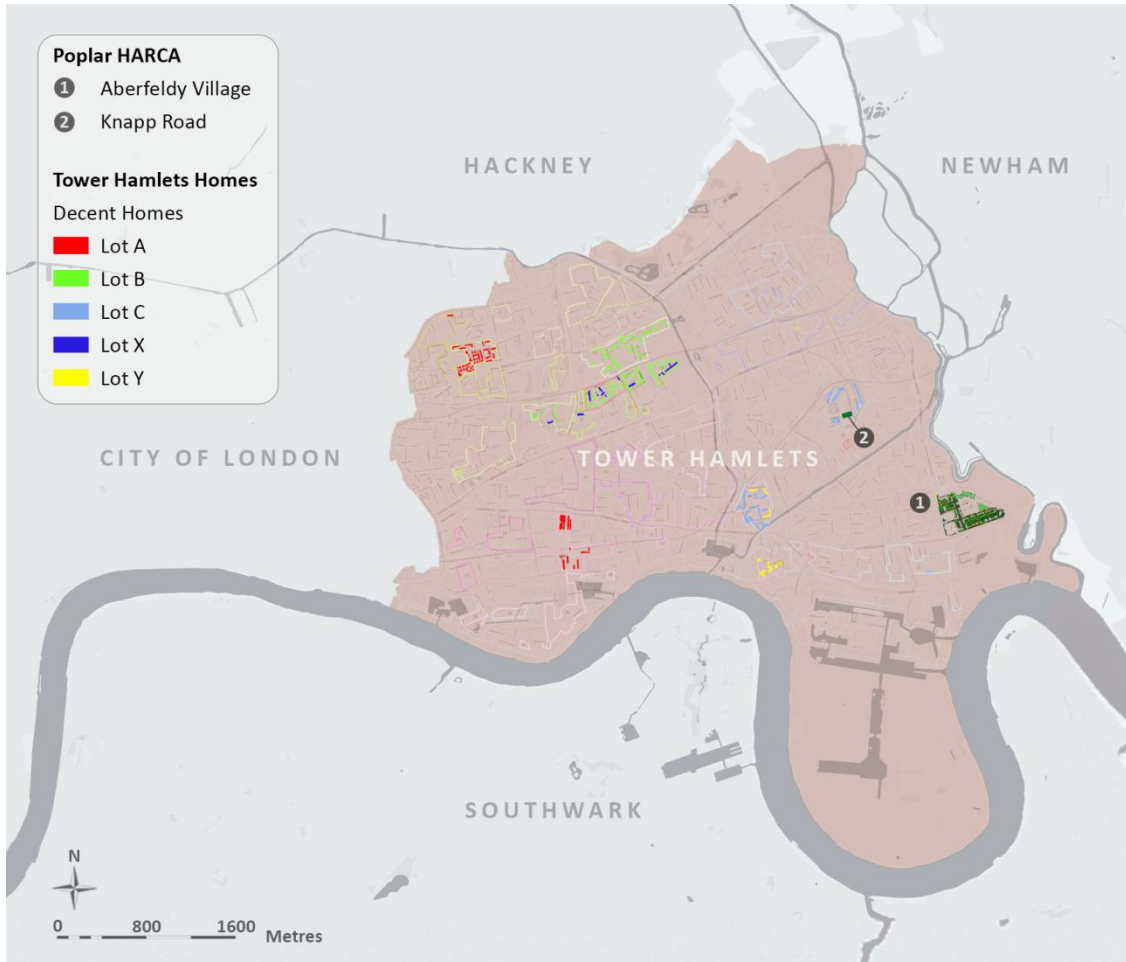


Figure 46: Map of the London Borough of Tower Hamlets and surrounding boroughs showing site locations

Decent Homes

Tower Hamlets Homes's Decent Homes programme is a series of individually small refurbishment works, spread across the Borough and divided into five 'lots'. These were tendered separately and are being undertaken by five different contractors. Lots A, B and C contain internal works to an average of around 2,200 properties (including replacement of kitchens and bathrooms), and external works to around 3,700 properties (including replacement of windows and doors and upgrading of roofs). Lots X and Y each contain internal works to around 600 properties. The contractors for these lots are smaller companies. From 'opening' to 'closing' a flat, including snagging and handover, takes twenty days.

The widespread array of individual properties and quick turnover of works necessitates a scattered and fast-moving construction process without the focus lent by the normal, fixed site boundaries. During the works most residents retain access to their flat outside of contractors' work hours. The logistics of material movements are therefore critical. Contractors have central site compounds, where, along with their site offices and welfare, strip out waste is usually consolidated and new purchases are stored ready for installation.

Responsive maintenance

Tower Hamlets Homes have a responsive maintenance contract with a large contractor that carries out unplanned, small-scale repair works on a call-out basis. Individual operatives attend several properties per day, with jobs such as repairing taps and replacing broken windows taking an average of two hours. They also carry out clearances of disused flats, which can last up to ten days.

N. Methods of data collection and analysis used in the case studies in Rose and Stegemann (2018a)

Data collection

The initial case studies were approached with the principle of triangulating from several sources of evidence (Yin, 2014). This allows the researcher to reach more accurate and reliable conclusions. Of Yin's six sources of evidence, documentation, interviews and direct observations were identified as the most pertinent for the study.

Documentation

The documentation collected for the case study projects includes SWMPs and waste reports (to establish how much of different waste streams are being produced, the names and locations of the various companies who manage these waste streams, and the proportions sent to landfill, energy recovery, recycling and reuse); and waste management companies' lists of ultimate disposal sites and the websites of the companies running these sites (to track the routes of waste streams downstream). Telephone communications with some of these companies was necessary to establish where the chains of recycling processes ultimately lead.

Limitations and procedural issues

The waste reports do not represent a complete set of information about all case study projects. Decent Homes contractors are obliged under the contract prelims to maintain a SWMP, including 'a full record of the quantities of waste produced', and 'to ensure that the SWMP is regularly updated during the progress of the works'. However this is rarely prioritised by contractor or employer and as a result is frequently disregarded, or only partially fulfilled.

Where records have been made available, weaknesses remain in the data. In some projects, different subcontractors use different waste transfer stations. The presented data account for the waste received at the primary waste transfer station, as reported by the contractor, but may not include all waste generated. Excavation waste is excluded because the sheer mass of inert material arising crowds out important distinctions between materials of higher value, where there is more scope for improvement on current practices. Hazardous waste and sewage from site welfare facilities are also excluded from the study. Some waste management companies report only 'mixed C&D waste', and when quantities are broken down the categories are not precise enough to provide an informed picture of the state and quality of resources. We will assess this issue in more detail in the next chapter.

Semi-structured interviews

A semi-structured interview process was adopted to allow the interviewer to tailor the language and approach to suit differing projects and interviewees, and to allow the discussion to follow a path led jointly by interviewer and interviewee, whilst ensuring that core topics are covered. An interview length of at least 60 minutes was sought so that the complexity and character of issues could be investigated in depth (McCracken, 1988). Some interviewees were unable to offer that length of time. The shortest interview lasted fifteen minutes and the average length was 48 minutes. Interviews were carried out over a period of several months. As the projects are ongoing, this timeframe encourages a non-linear, iterative approach, in which interviews with different members of the project teams can follow after reflection on the testimony and on new direct observations and assessment of new documentation. The reflection periods allow the interview template to be continually developed and refined.

Previous research has looked at waste in relation to individual workers' behaviour (Teo and Loosemore, 2001), and from a design perspective through surveys of architects (Osmani et al., 2008). As the present study focuses on systems of managing waste, interviewees were selected from management positions within client organisations, contractors and waste management companies (Table 12 in section 4.2.1).

Limitations and potential problems

Wherever possible, several people from each case study projects were interviewed to address the risk of an individual holding a biased viewpoint, and having limited memory recall. Across different projects and with different interviewees, the same topics are covered, increasing confidence in the testimony.

As a representative of the contractors' client, the author as interviewer may be perceived to be interrogating the performance of the interviewee's company. To encourage in the interviewee a less guarded attitude, it was clarified at the start of interviews that the study is part of a research project for both Poplar HARCA and Tower Hamlets Homes, and that we are seeking to understand the broader industry, not find fault with individual contractors. Interviews were not recorded out of a concern that to do so would inhibit interviewees from speaking freely, in particular when discussing weaknesses in their company's practices. Treating the situation like a meeting or informal conversation improved 'ecological validity' (Bryman, 2012: 48): it allowed the researcher-interviewee relationship to feel more familiar and data gathering to arise more naturally from participants' normal activities. Short notes were taken while conducting the conversation, as one would in a meeting, including occasional verbatim phrases. A salient transcript of the conversation was ensured by writing up a thorough account immediately after the interview, noting down other verbatim phrases and making sure all the main areas of conversation were covered by referring back to the interview structure. These were reviewed 1-

2 weeks later after a period of reflection. Confidence in the transcript could have been improved by having someone else fully transcribe audio recordings, to avoid misrepresentation being made through the researcher's own impression of what was said (McCracken, 1988). Full transcripts, though time consuming, would have kept open the option to use computer-assisted qualitative data analysis software to analyse the interview testimonies, had this come to be considered a useful approach to the project.

As an architect, the researcher could be accused of holding preconceived views about contractors' attitudes. While this background cannot be suppressed entirely, the role of objective researcher was adopted as far as possible. The researcher had no existing relationship with contractors that could lead to personal bias.

Interview template

Below are the questions that form the framework of the interview. 'Grand tour' questions (McCracken, 1988; shown numbered) open the main topics of discussion and are intended to allow the interviewee to explain a situation in their own terms. 'Floating prompts' and 'planned prompts' are used as necessary to elicit expansion of responses (McCracken, 1988; planned prompts shown bulleted).

Intros

1. Can you tell me a bit about [the company]?
 - Where do you operate?
 - Are there a lot of projects going on at the same time?
 - What's your role / background?
 - How much of your time is working on [this project]?
 - How's your workload week-to-week?

Subcontractors

2. Are there subcontractors that you work with all the time?
 - Ongoing relationships?
 - Are they big companies / working locally?
 - How many different subcontractors are working on site at the moment?
 - How is the waste managed between them?
 - Do you / they have a yard somewhere for storage?
 - Was there a separate demolition contract?

Waste management

3. How do you deal with waste arising on a project?
 - What causes the most waste?
 - Do you segregate waste on site?
 - Do you always use the same waste management company?
 - Where are they based?

- Where does it go after the WTS?
- How much does it cost to get rid of your waste?
- Do you mind if I contact them and would you like to join me on a visit to WTS?
- Do you work with any reuse organisations?

Waste reporting

4. Who produces the waste reports for this project?

- How is the waste measured?
- Are you still using SWMPs now that they've been withdrawn?
- Can you send me all the project waste reports and copy me in when you issue them in future?

The waste hierarchy

5. How do you go about complying with the waste hierarchy?

- Waste transfer notes require waste handlers to indicate that they have complied with the waste hierarchy - what do you do to comply?
- How can you prevent or minimise waste?
- How can you reuse materials and components?

Reuse

6. Has there been any reuse on this project?

- Have you reused materials and components in the past?
- What are the barriers to reuse?
- How would you make reuse more common?
- Do rising landfill costs make a difference?
- Is resource scarcity or rising costs going to be an issue in future?

Reuse material markets

7. Do you use, or have you thought of using, one of these sites (Recipro etc.) to pass on surplus materials and products?

- Are they useful?
- Why don't / wouldn't you use them?
- How do they fit in to your waste management procedures?

Considerate Constructors Scheme (CCS)

8. Are you part of a CCS scheme?

- Have you had a visit from CCS?
- What comments did they make on waste?
- Has anything changed since?

Direct observations

Direct observations of the case study projects included attendance at progress meetings (in order to gain an introduction to key staff from contractors), weekly attendance at the offices of Poplar HARCA and Tower Hamlets Homes, site visits, and visits to waste transfer stations. Site visits were carried out regularly and provided opportunities to discuss informally with junior site

managers, foremen and labourers, and observe the reality of site practices. Seeing and moving through the spaces makes the processes discussed in interviews more tangible. This is even more vibrantly the case with visits to waste transfer stations – unfamiliar places at the edges of cities – where the speed and brutality of waste movements brings colour to the numbers in a waste report.

Analysis

The first stage of analysis was the creation of a case study database of all data collected. This is available on request in order to allow the data to be scrutinised by the critical reader. From the raw data gathered in the case study database, the analysis of numerical data involves the establishment of a consistent framework for diverse forms of waste documentation. This provides a means of collating and comparing the waste generated in different projects, leading to charts and a diagram that explain the general picture for all case studies. Raw data from interviews in the case study database are coded under emergent thematic clusters. Interviewees' responses on each theme are compared and contrasted, leading to the identification of a series of common concerns and issues. These are interpreted alongside direct observations and the picture developed from waste documentation to draw out an understanding of the reasons for the predominance of the current waste management system.

The next stage of analysis categorises the findings into types of problems and barriers that would need to be overcome to improve on current practices. A 'problem tree' and 'objective tree' technique is used (Mosard, 1982; M. Davies, pers. comm. 21st July 2014) to assess causation within each category, and to provoke visions of how the world would be different with the solving of each problem (Figure 47).

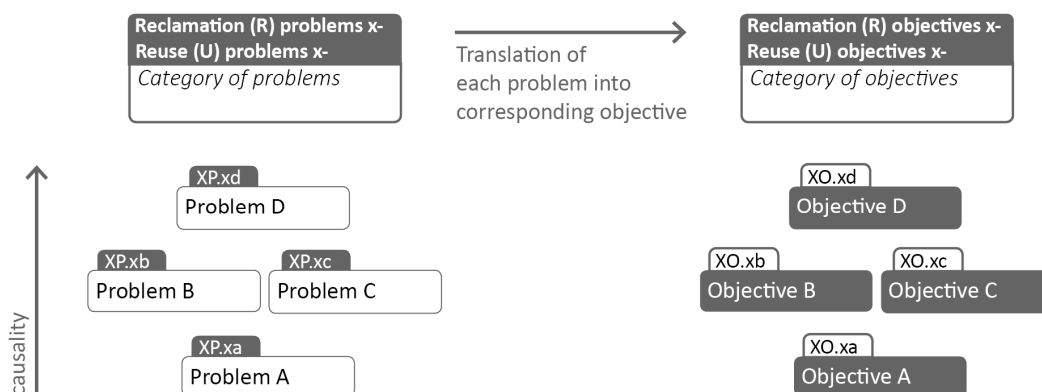


Figure 47: Interview analysis – key to problem trees and objective trees used in analysis

The problem and objective tree framework spurred ideas for how problems might be addressed, but did not provide a legible progression from testimony to interpretation to proposals. Some months later, the researcher returned to the interview data and took a different analytical

approach: mind mapping the thematic clusters identified in the earlier stage of analysis. This ultimately was represented as Figure 48, which attempted to link reported barriers to underlying causes and develop a logical approach to identifying areas for focus. A further return to the data in pursuit of greater clarity led to Table 30 in Appendix P.

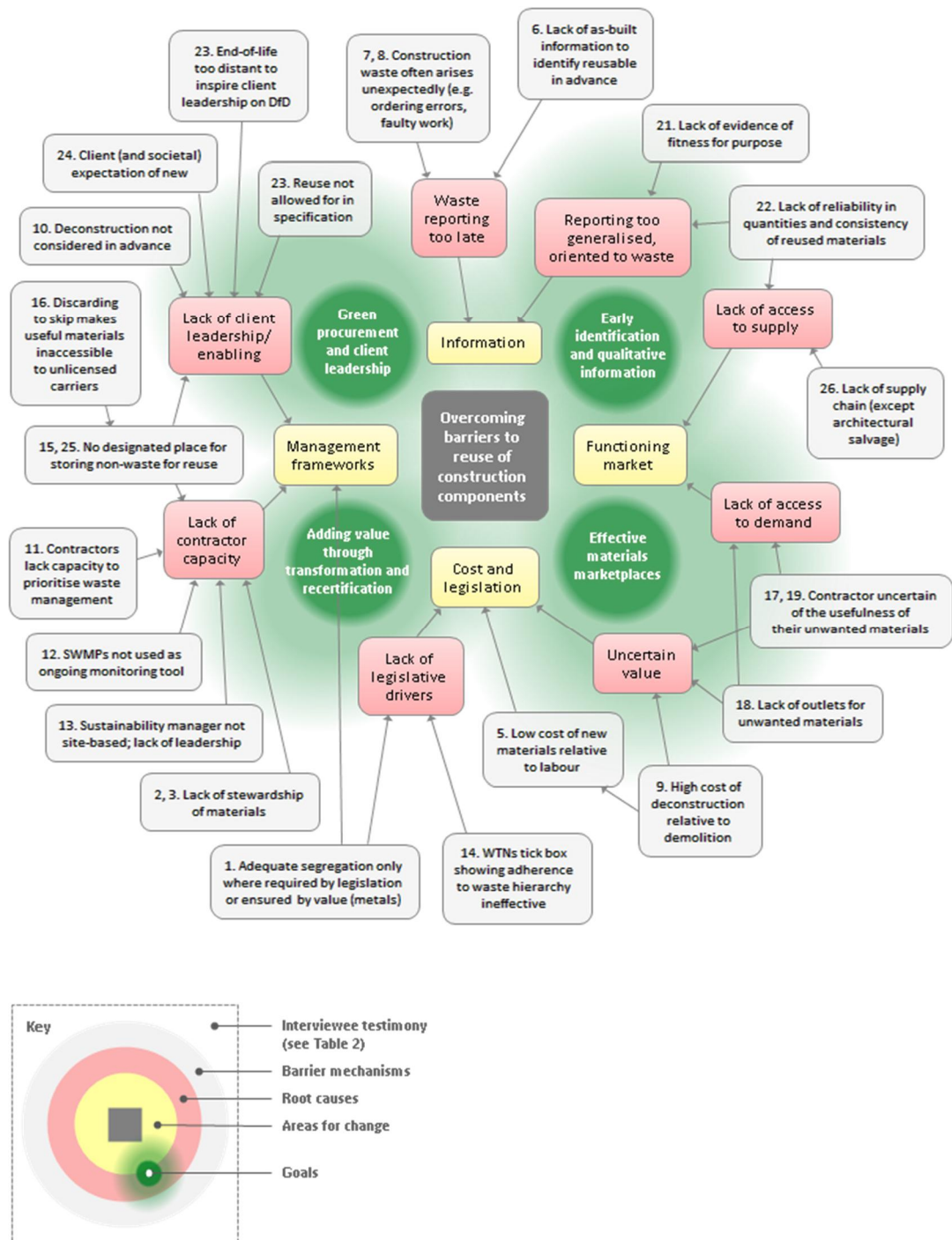


Figure 48: Interview analysis – diagram resulting from mindmapping exercise

O. Selected analytical diagrams

Data gathered in this project frequently were not textual; drawing diagrams was a critical analytical activity throughout for re-presenting information to encourage new interpretations, and for exploring systemic links. The diagrams that remained most relevant as the research proceeded are reproduced in this appendix.

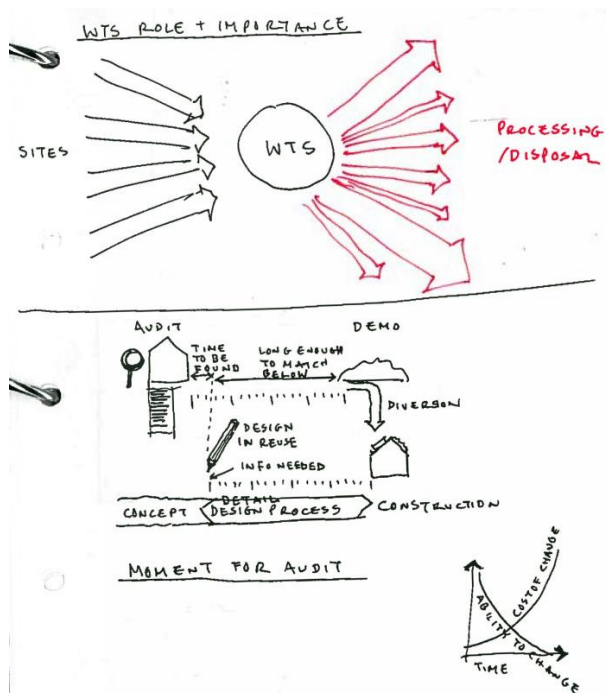


Figure 49: The central role and importance of waste transfer stations in C&D waste management and the significance of the timing of pre-redevelopment audits

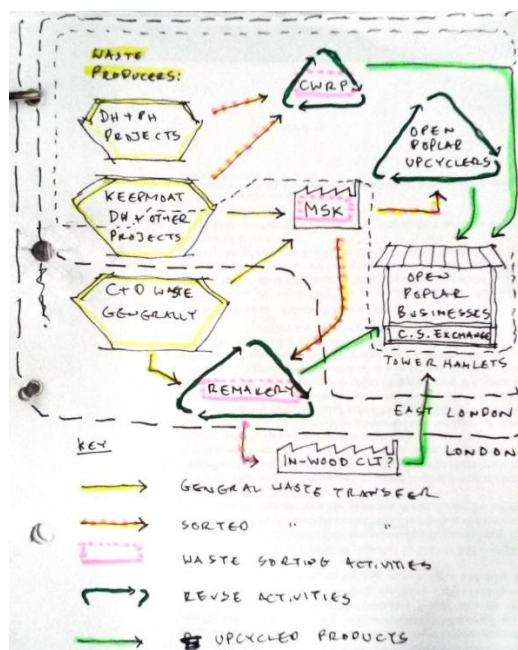


Figure 50: C&D waste and material flows related to industrial sponsors, in Tower Hamlets and London

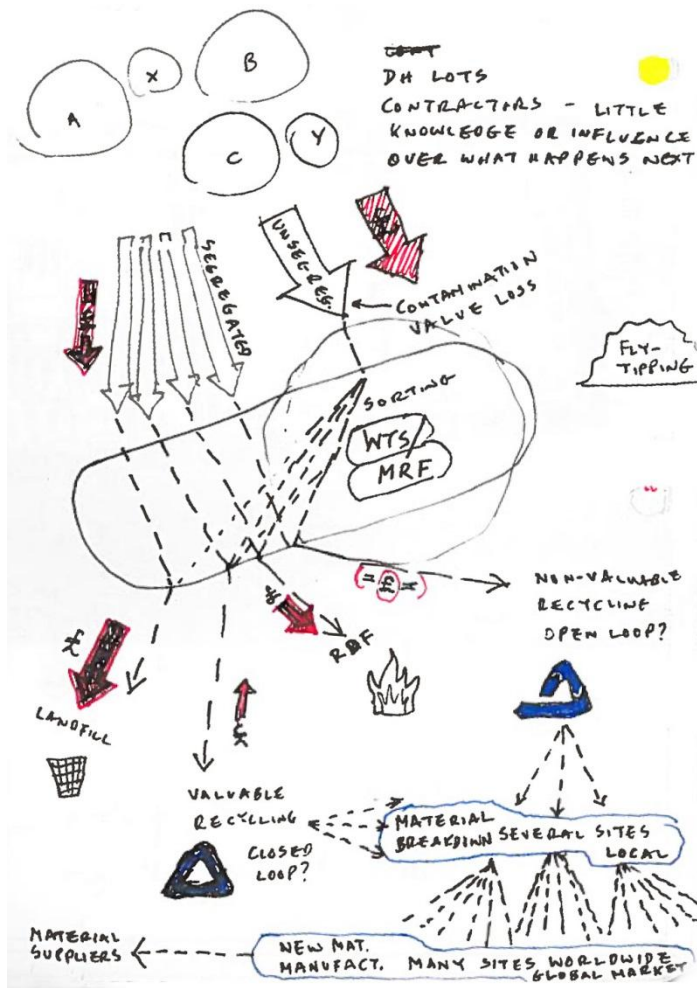


Figure 51: First model of existing C&D waste management based on Chapter 4 case study observations

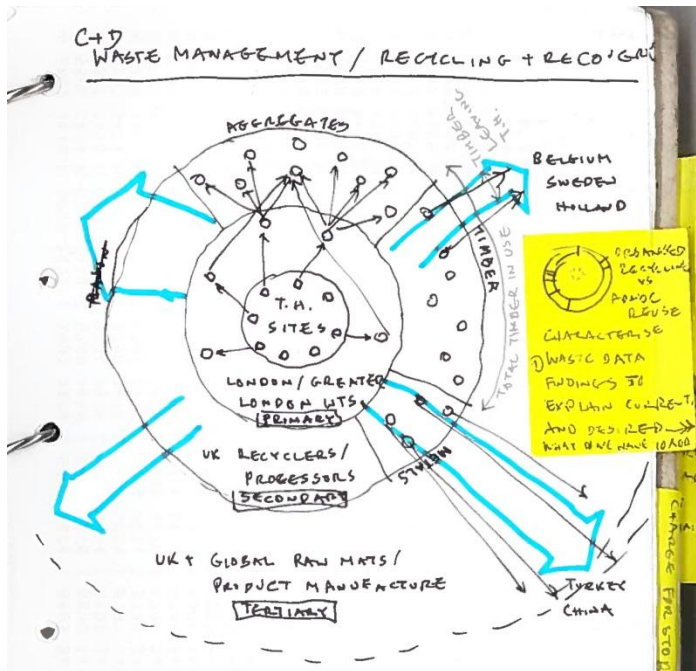


Figure 52: Second model of existing C&D waste management, introducing geographical analysis – local at centre

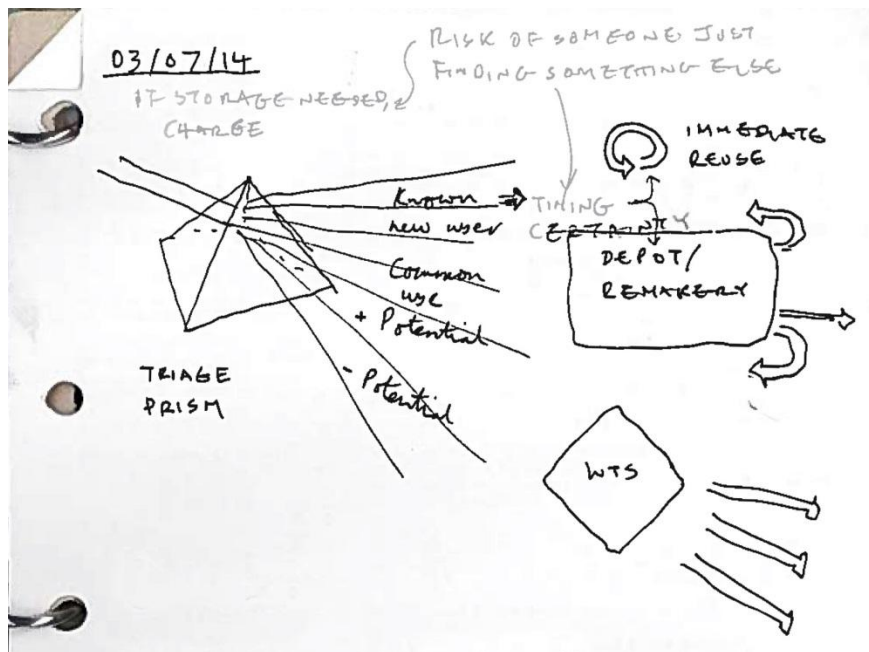


Figure 53: First idea of triage as a prism separating out streams of reusable and non-reusable components

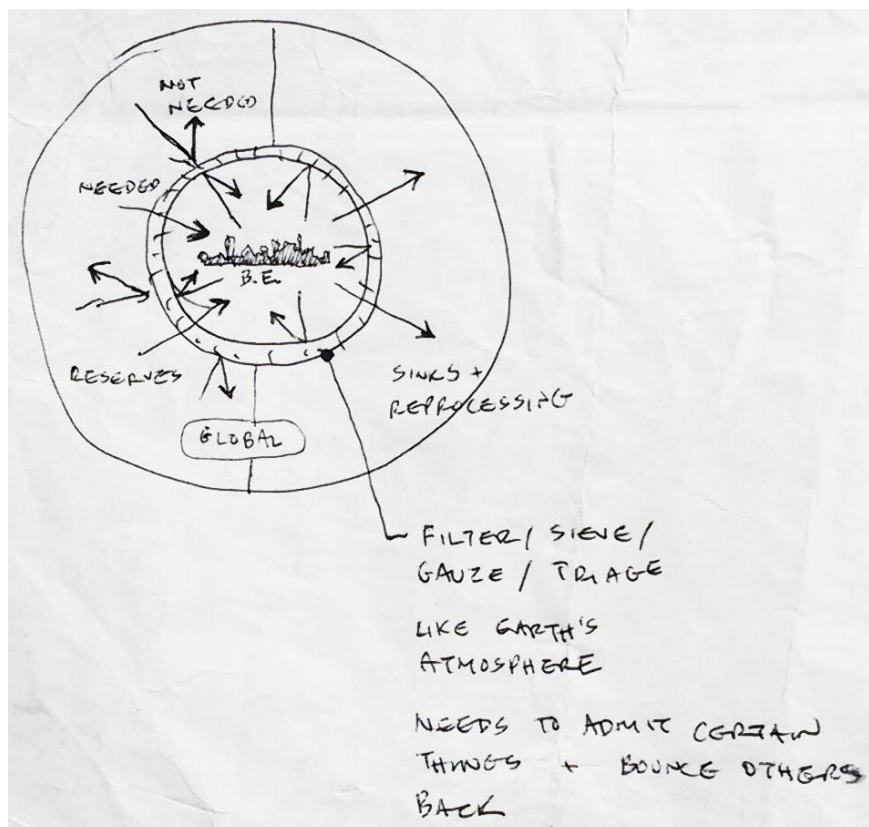


Figure 54: Second idea of triage as a filter bouncing reusable components back into the local economy, and allowing non-reusable materials to pass through to waste management beyond

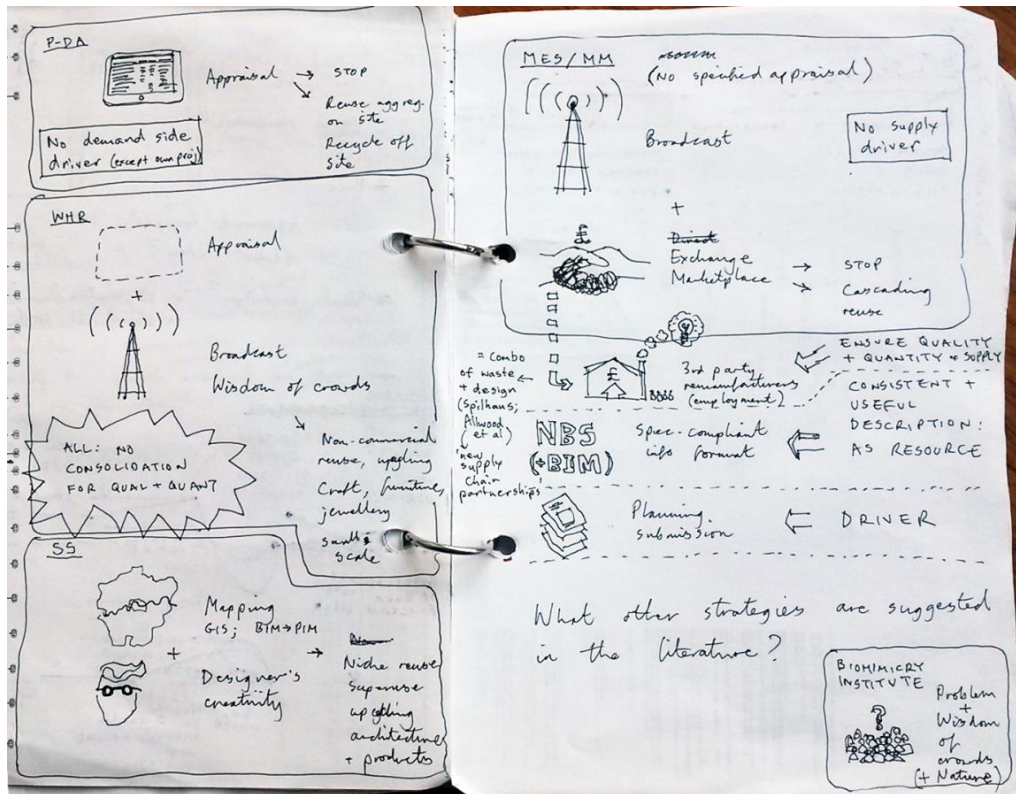


Figure 55: Early ideas of elements in an E-BAMB information system

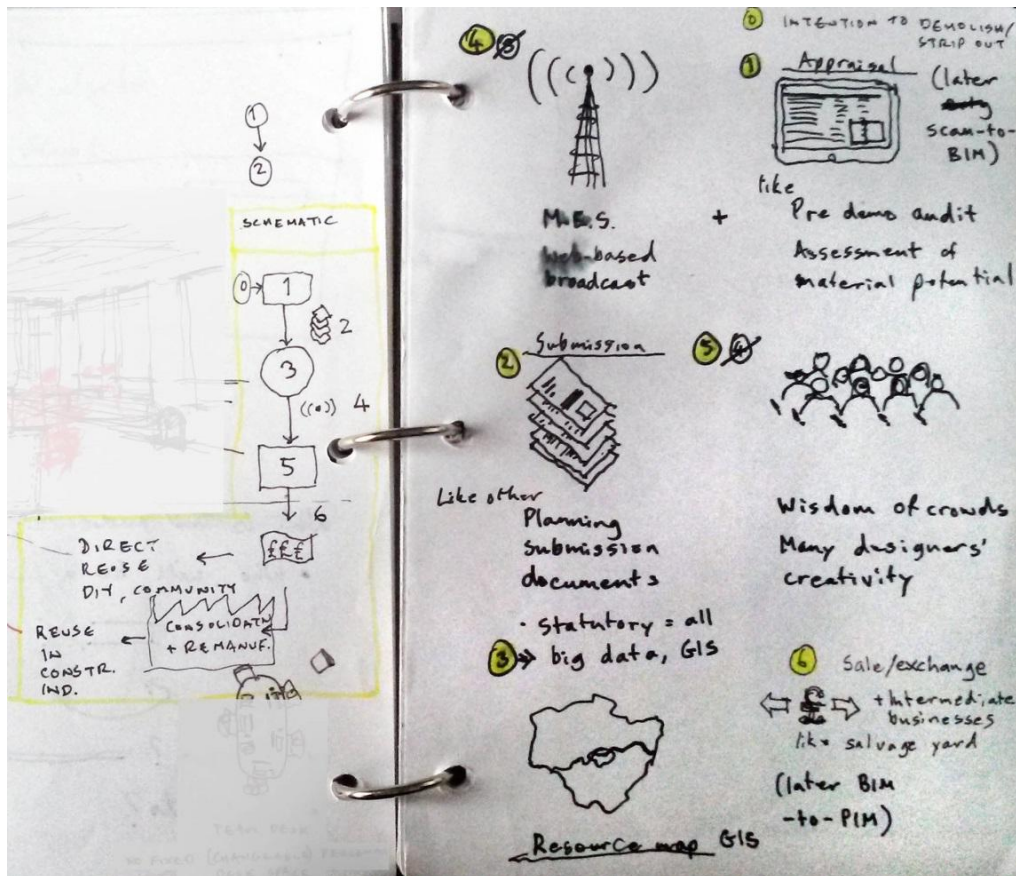


Figure 56: E-BAMB information system design

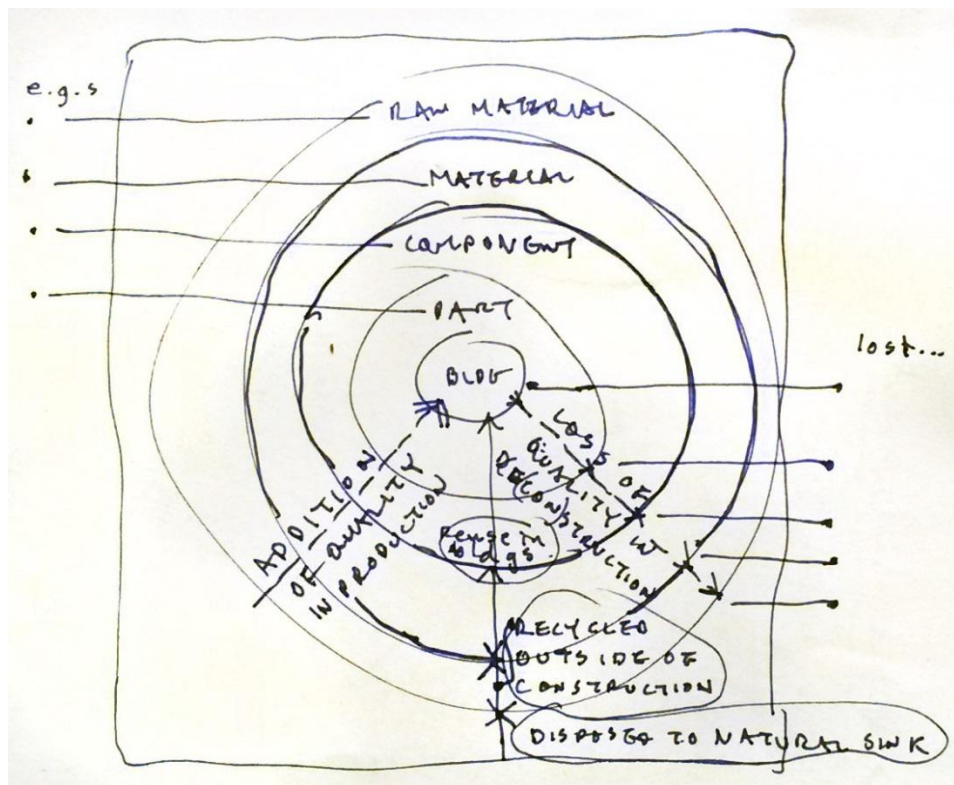


Figure 57: Hierarchy of building element performance – the complete building at the highest point in the centre

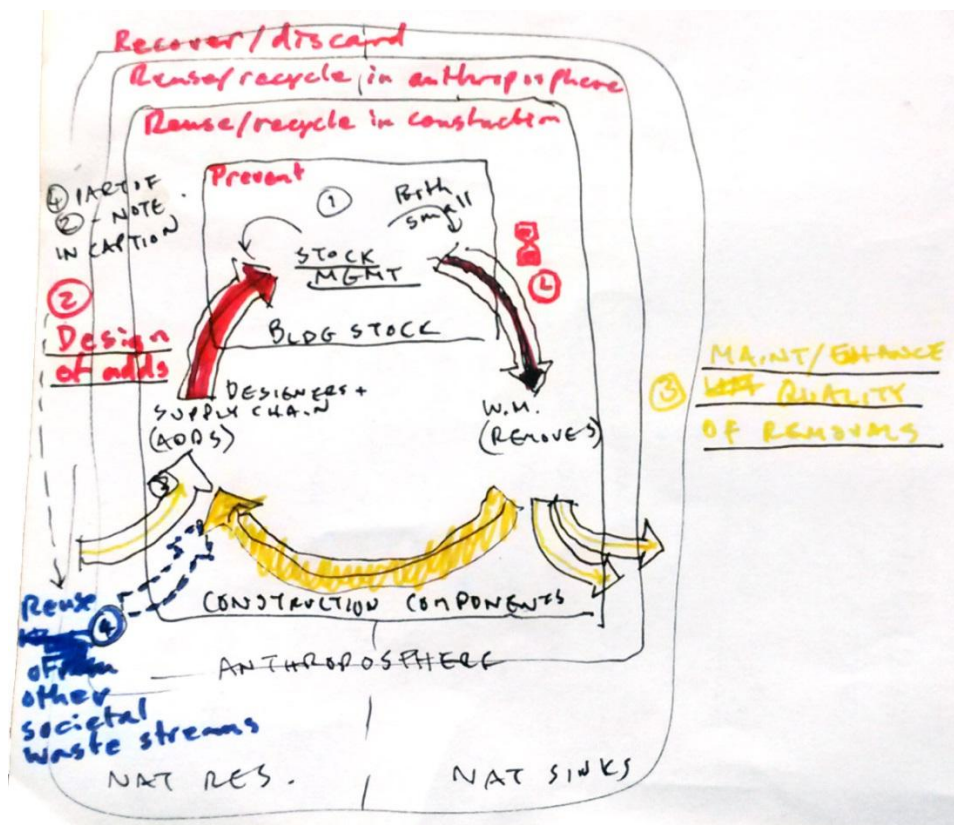


Figure 58: Means of managing C&D materials to retain performance – building stock management at the centre

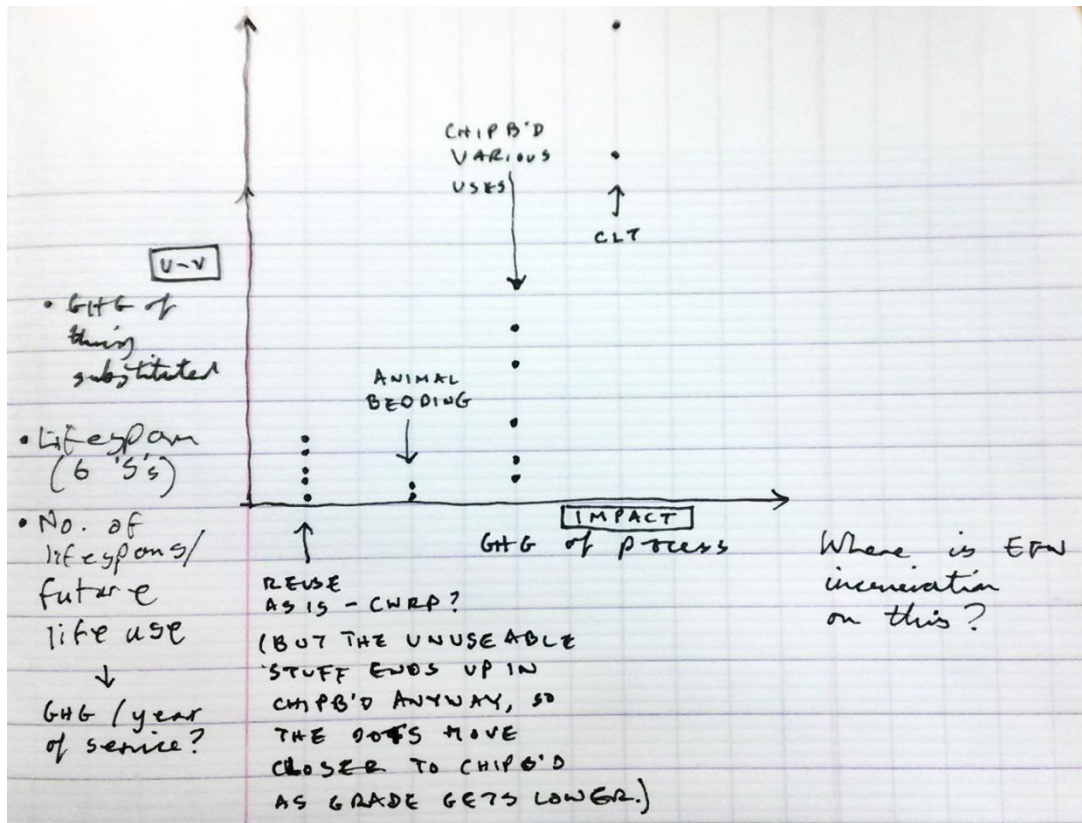


Figure 59: Illustrative graph mapping different waste or component management processes, with process impacts on the x-axis against secondary product performance (or 'use-value', as conceived at the time, measured by the impacts of the displaced primary product) on the y-axis

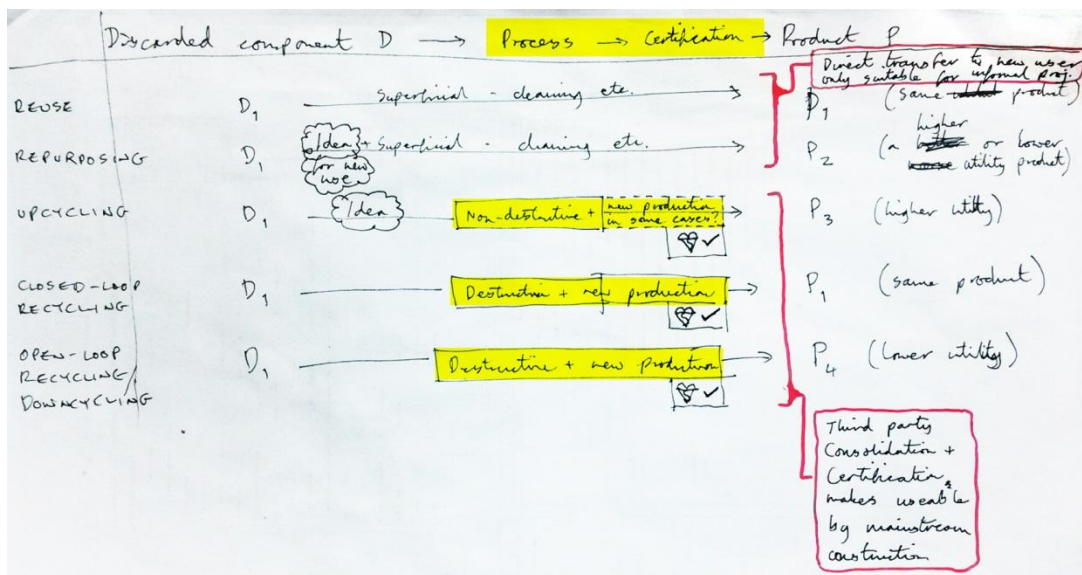


Figure 60: Different waste or component management processes – secondary material inputs, processes and product outputs, achieved with or without the involvement of a third party intermediary

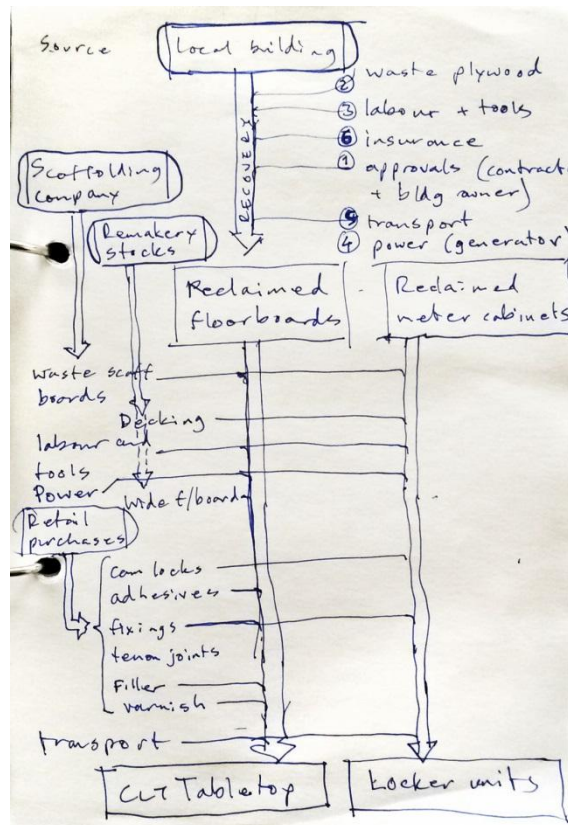
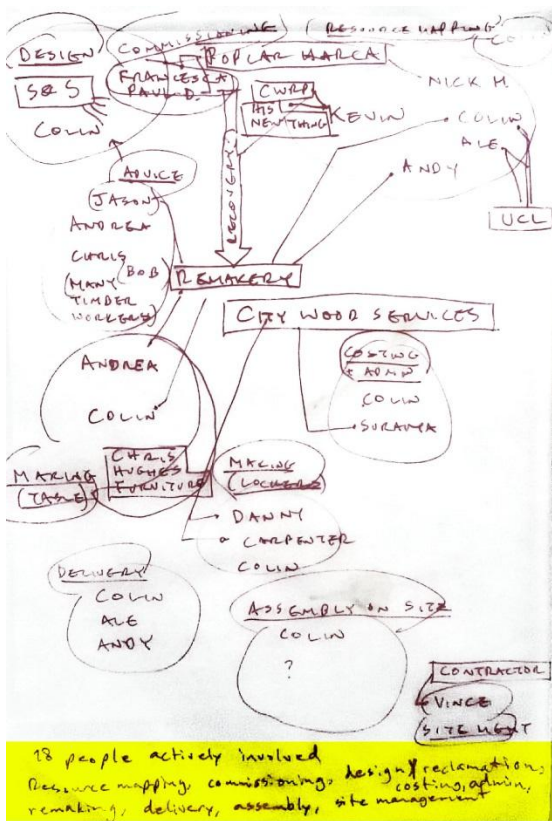


Figure 61: Chrisp Street Exchange case study roles map

Figure 62: Chrisp Street Exchange case study resource flows

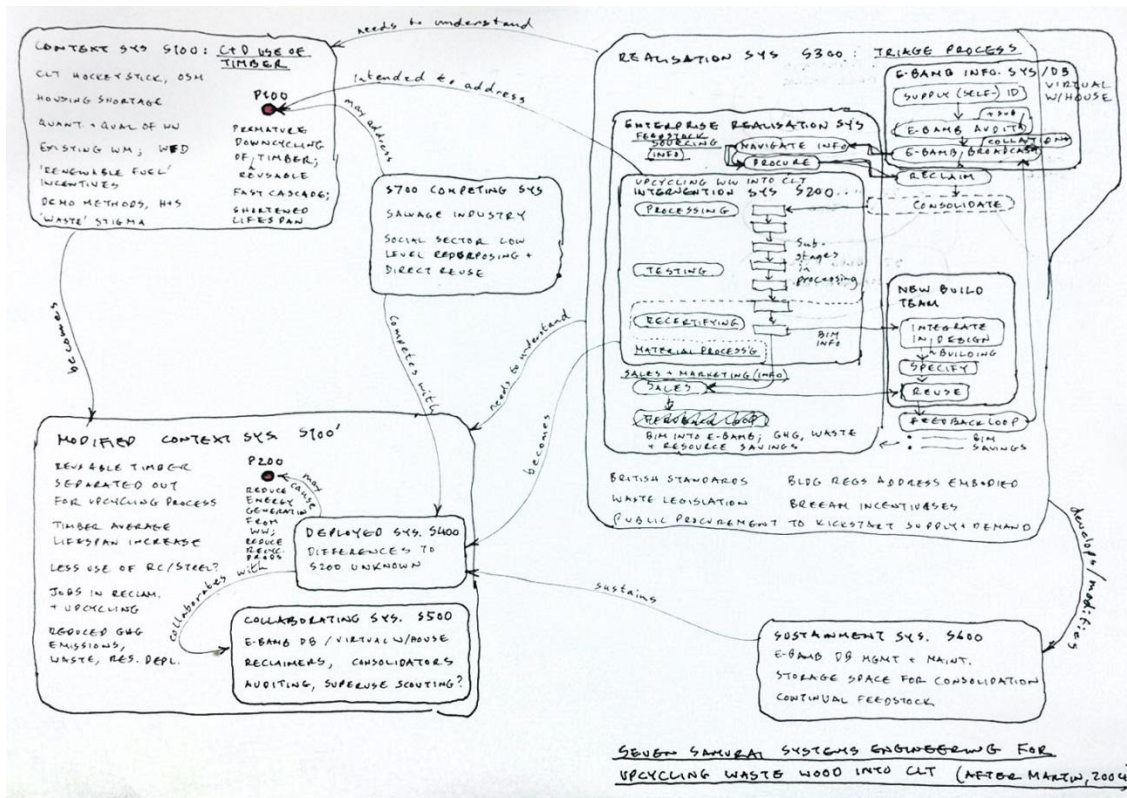


Figure 63: Cross-laminated secondary timber systems engineering diagram, after Martin (2004)

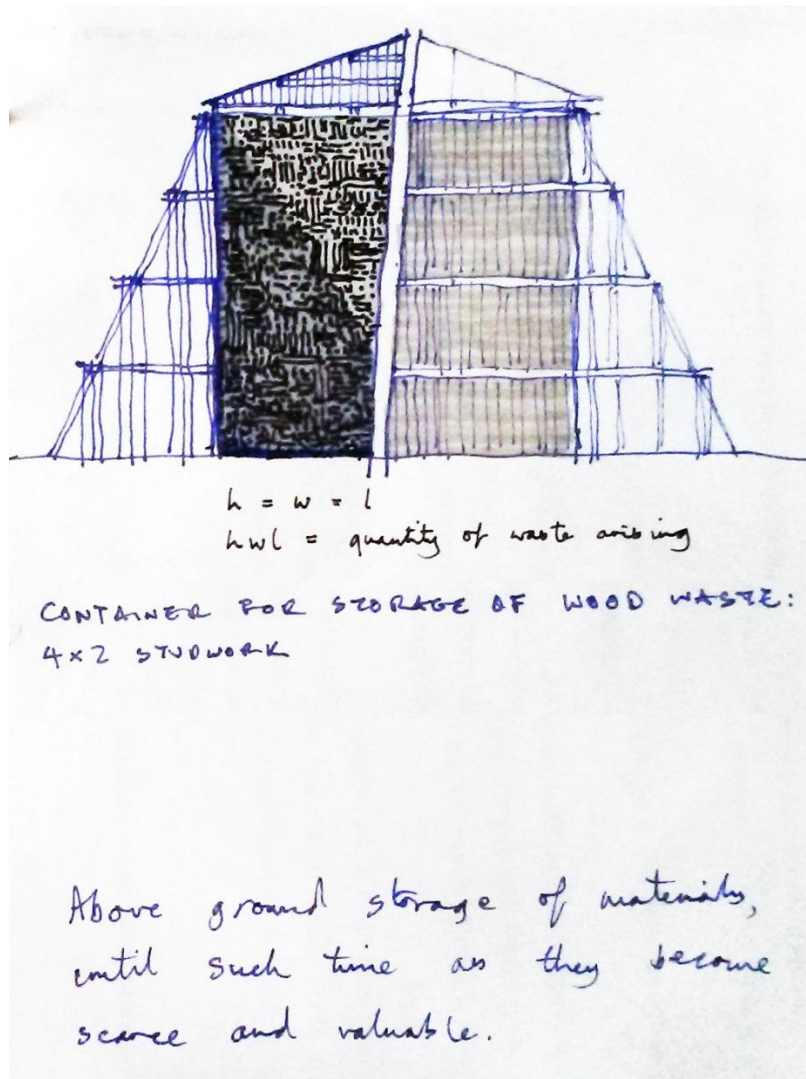


Figure 64: Above ground storage of materials, instead of landfill, as a visible landmark of waste

P. **Supplementary information published with Rose and Stegemann (2018a)**

Table 1: Summary of findings from interviews with contractors, waste management companies and client organisations

No.	Interview topic	Sample of interviewees' testimonies	Authors' observations and interpretation	Suggested <i>driver</i> /barrier mechanism	Suggested systemic factors
1	Waste transfer notes (WTN) and the waste hierarchy	'Compliance with waste hierarchy' tick box on WTN at point of waste transfer is too late to be effective; already discarded to skip, potential demand not reached/heard; better if built in as something the sustainability manager actively governs (RC, NBL).	'Prepare for reuse' stage of hierarchy unlikely to be taken unless there is confidence that it will beneficially lead to reuse. Site workers have the potential to identify opportunities for on-site reuse; sustainability manager may see opportunities elsewhere in company; but off-site reuse by others cannot reliably be anticipated from contractor's vantage point.	WTNs tick box showing adherence to waste hierarchy not supported by system to enable compliance; uncertain value/demand	Weak regulatory legislative drivers; lack of systems thinking
2	Deconstruction – cost and programme	Taking building down by hand not specified by client, more expensive because it takes far more time and has health and safety issues (NBS). Required time for deconstruction will not fit with programme (PH), and is unlikely to result in anything that can be reused (PH).	There are sometimes instances of buildings made vacant but projects on hold, which could allow at least soft-strip to commence. Not clear that time invested will be paid back in sale of components unless demand is established first. Assumption that there would be no demand remains untested.	Deconstruction not considered in advance; high cost relative to demolition; uncertain value/demand	Item 3; lack of client leadership/ enabling; buildings not designed for deconstruction
3	Cost of new versus reused	Very cheap these days to get new materials (PH).	Client expectation that reused should be cheaper than new; difficult to achieve in practice without mature supply chain, given lack of economies of scale and probable labour intensity of reuse.	Low cost of new materials relative to labour	Lack of economic legislative drivers; lack of mature supply chain
4	Offering materials for reuse – arranged end-user	Useful materials end up in the skip (NBS, RC, THH); much good quality timber and plywood arrives at WTS (WM1, WM3). Old timber, doors etc. previously given to carpentry apprentices for practice (RB, RX); but no consistency of demand and no time to identify other users (RB). Space and time constraints at WTS prevent setting aside for reuse (WM1, WM3).	Those managing construction often started as trades-people, working with materials; they do not like to see good materials go in the skip. But personal moral/emotional reasoning is overridden by company/project demands. However, companies are very aware of their public reputation; if inconvenience is minor, willing to offer materials to local community groups.	Lack of outlets for unwanted materials; contractor uncertain of usefulness of materials <i>Driver: Corporate social responsibility</i>	Separation between supply and demand; uncertain value
5	Offering materials on reused materials marketplaces (RMMs)	Some have used RMMs (NBL, RC); some have heard of but not used (NBS, WM2); some are not aware (RX). Off-putting associated costs in temporary storage and managing site during collection (NBL). Takes time to post items on websites, with no guarantee that anyone will want, or taker may fail to collect (NBS).	Individual on site has bounded knowledge of what is useful elsewhere; he may waste time offering things that are not wanted, and dispose of things that are wanted. Trust between person offering material and person taking material on RMM could be established through member profiles.	Contractor uncertain of usefulness of their unwanted materials	Separation between supply and demand; uncertain value
6	Reusing materials – RMMs as supply	No recognition of where to find reused general building components – only specialist architectural salvage (RC). Those familiar with RMMs sceptical about achieving spec compliance (NBL, RC); lack of warranties (NBL); quantities needed not available at right time from single source (WM2). Extensive certification of new products deters use of reclaimed (RX).	Designers not familiar with specifying from RMMs. Mainstream industry requires materials to be certified to ensure consistent quality. Recertification not common practice. No known examples of value-adding reuse enterprises. If RMMs paired with existing infrastructure of builders' merchants they could sell recertified materials alongside new to normalise the idea of reuse.	Infancy of supply networks (except architectural salvage); lack of reliability in quantities and consistency of reused materials	Lack of client leadership/ enabling; high cost of land relative to materials; uncertain value
7	Reusing materials – time to use	Inadequate stocks and lack of consistency in reused components makes finding and working with them more time consuming, and often a more skilled task (WM2).	Contractors almost always struggling to keep up with construction programme; consolidation needed to ensure reasonable lead-in times and stocks as consistent as new.	Lack of reliability in quantities and consistency of reused materials	Items 3 and 6
8	Reusing materials – product information and quality	Reclaimed materials lack information about any toxicity, previous stress for structural elements: do not know what they are working with (NBL). Residents are expecting new, that is what client has paid for; doubts over aesthetic qualities of reclaimed materials (RX).	Reclaimed materials are considered something of an unknown; e.g., there may have been changes in safety standards during lifespan of original use. Need for prototyping during design stages to test aesthetic acceptability (like getting samples of new materials).	Lack of evidence of fitness for purpose; client (and societal) expectation of new	Items 6 and 9; reporting oriented to waste; lack of client leadership/ enabling
9	Causes of waste – lack of 'as-built' building information	Lack of data about what is in buildings leads to waste (RMW): e.g., in refurb strip out, collection of white goods by reuse enterprise needs 72hr notice period and contractor cannot foresee or store (RC).	Reusable resources identified too late in the process to be acted upon.	Lack of as-built building information to identify reusable in advance	Buildings outlive as-built info; waste reporting does not provide substitute
10	Reusing materials – compliance and contractor influence on design	Employer's Requirements calls for FSC/PEFC (i.e., certified new) timber; considered non-compliant to use reclaimed; no scope to change design (RC). Contractor will not make a tender offer 'more green' than it is required to be (RB); may challenge design but 'must be competitive on the client's terms' (NBL).	Contractors often have limited ability to influence design; reuse needs to be built into or explicitly allowed in client's specification. Perception that 'green' always comes at a price premium.	Reuse not considered during design stage, not seen as realistic option	Lack of client leadership/ enabling; lowest price tendering
11	Offering materials for reuse – unlicensed carriers	Sometimes people see useful materials in a skip and take, or ask to be put to one side then fail to collect (NBS); employees on site sometimes take away surplus for use on private jobs (RC).	Demonstrates demand for and usefulness of materials. Duty of Care means this type of reuse is a grey area legally; informal agreements with public can inconvenience contractor if abused.	Discarding to skip makes useful materials inaccessible to unlicensed carriers	Item 12; lack of formal connection between supply and demand
12	Offering materials for reuse – storage space	Rarely enough space for segregated waste streams and reuse storage (WM2, NBS, RC). Construction produces things that could be reused, but not immediately by contractor at time of needing to dispose (NBS, RC); if a dedicated storage space was provided off-site it would help facilitate (NBS, RC).	Blocks of flats sometimes contain unoccupied flats that could be provided as short-term, small-scale storage during works to neighbouring properties; would need management regime. Could also bridge gap with collection by reuse enterprises, as items 5 and 9.	Large spaces rarely available in inner city locations; designated place for storing non-waste for reuse not prioritised	Uncertain value; lack of client leadership/ enabling
13	SWMPs	SWMPs encourage forethought, provide framework for monthly reporting, still using for new projects despite withdrawal (NBL). Forecasting gives contractor an idea of the amount of waste they're likely to generate (WM2).	SWMPs badly maintained as ongoing monitoring tool on refurbishment projects and NBS (doc.): only prepared in fulfilment of tender requirement or used only at pre-construction planning stage.	Outsourcing of reporting to waste management companies	Lack of contractor capacity

No.	Interview topic	Sample of interviewees’ testimonies	Authors’ observations and interpretation	Suggested <i>driver</i> /barrier mechanism	Suggested systemic factors
14	Sustainability manager	Office-based employee leads on sustainability, overseeing many projects (NBL, RA, RB, RC, RX, RMW).	Lack of site-based sustainability expertise; and lack of site experience on the part of sustainability expert. Usually compliance monitoring role more than driving innovation.	Contractors lack capacity to prioritise active sustainability leadership	Lowest price tendering; lack of systems thinking
15	Cost of disposal	Full 12yd skip costs £200 to remove from site (WM1); most materials continue to attract fee for removal from WTS (WM1, WM3); incineration costs almost as much as landfill (WM1).	Landfill Tax has rendered even recyclable waste (except metals) a liability; this opens up opportunities to find value in resources.	<i>Driver: Opportunities to add value by upcycling and recertifying</i>	<i>Escalation of Landfill Tax</i>
16	Intra-company material exchanges	Material exchanges between projects of different scales – example of stripped out carpet tiles from one project used in site office of another (NBL). Builders’ merchants run as part of business (RX) or by sister company (RWM) to re-stock unused surplus.	Potential to cascade uses of materials within company from one project to another at present uncommon and limited to the contractor’s own site accommodation. Other leading large contractors beginning to introduce internal RMMs to bring about intra-company reuse practices.	<i>Driver: Desire to avoid disposal costs, reduce carbon footprint and show innovation</i>	<i>Item 15; contractor competition</i>

Abbreviations: RA = contractor for refurbishment Lot A; RB = contractor for refurbishment Lot B; RC = contractor for refurbishment Lot C; RX = contractor for refurbishment Lot X; doc. = finding from documentation; PH = staff from Poplar HARCA; NBL = contractor for large new build project; NBS = contractor for small new build project; RMM = reused materials marketplace; RMW = contractor for responsive maintenance works; SWMP = site waste management plan; THH = staff from Tower Hamlets Homes; WM1 = waste management company 1; WM2 = waste management company 2; WM3 = waste management company 3; WTN = waste transfer note

Q. Description of observed C&D waste logistics from case studies in Rose and Stegemann (2018a)

Introduction

Tracy (2010) calls for the provision of ‘thick description, concrete detail, explication of tacit (nontextual) knowledge, and showing rather than telling’ as a criterion for the credibility of qualitative research. In pure social sciences, this might take the form of detailed descriptions of the relationships at play in a social situation. In this project’s sociotechnical context, a version of Tracy’s thick description was adopted in the reflection on and writing up of Chapter 4 case study projects. Observations across multiple cases were synthesised, with a focus on the logistics of C&D waste management. The commentary builds up a picture of how the current system of C&D waste management works, what waste streams are generated and where they end up, and how they are measured and reported by the parties involved. The main sources of evidence are direct observations of the places where waste is created, collected and sorted, and collection of documentation including waste reports and lists of ultimate disposal sites. An abridged version of this account is included in Rose and Stegemann (2018a), section 4.2 of the thesis.

Stages of construction waste management: site

At the site or site compound, all case study projects except one employ a skip service. Typically there is inadequate space to have different skips for different waste streams, except for the compulsory separation of hazardous and non-hazardous waste. Skips are provided by waste management companies who must be registered waste carriers. They collect full skips and replace them when requested by the contractor. The frequency of collection depends on the type and extent of work being carried out. Aberfeldy Village is the only project with the space to be able to make frequent use of segregated skips: of 198 reported skip movements over a seventeen month period, 134 were mixed waste and 64 were segregated (of which 47 were inert waste, six concrete, five gypsum/cement, four mixed metals and two hazardous).

The steps involved in the strip out waste from Decent Homes projects reaching the skip are more protracted than the new build projects. The process is captured in the series of photos in Figure 65. On the day a flat is opened, all the major strip out takes place and the resulting waste is carried to a temporary holding place outside the flat. Some heavy components, notably cast iron baths, present the contractor with a risk of manual handling injuries. This risk is mitigated by requiring heavy components to be broken up before they are removed.

From their temporary holding place, the various remnants of kitchen and bathroom are collected by a van or truck visiting all the openings of the day. Leaving out such a pile of waste for collection is expensive to the contractor in supervision (as well as bringing occasional

complaints from neighbours), so they will take it back to the skip at the site compound at the earliest opportunity. Lot X of the Decent Homes programme is an exception to the use of a skip service: there, the day's waste is picked up in a small cage truck and taken directly to the waste transfer station.

Part of process specific to Decent Homes projects



Figure 65: Initial stages of Decent Homes waste management

Stages of construction waste management: primary sorting

Each waste management company employed by contractors in the case study projects runs a waste transfer station (WTS), where the primary sorting of waste occurs. These were all found to be within fifteen miles of the construction site. At the WTS the total weight of the skip contents is measured on a weighbridge. The waste is then tipped; segregated skips, straight onto the relevant pile, while unsegregated skips are added to a pile of incoming waste that goes through a series of heavy plant operations, trommel screening and manual sorting in order to separate the different waste fractions (Figure 66).

These are places of huge throughflow of material: skips will typically arrive at the WTS every 2-5 minutes. The operation only works, spatially and economically, if waste is continuously pushed through the system and out again, on the back of another truck, onto its next destination. Time and safety concerns prevent any more subtle, manual sifting of reusable components from taking place, and in any case the sheer physicality of the environment means that good materials are unlikely to avoid damage.

Part of process at waste transfer station



Figure 66: Primary sorting stages of construction waste management

Stages of construction waste management: secondary processing and beyond

The next step in the journey varies according to the material in question. Waste management companies send different waste fractions to appropriate 'ultimate disposal sites'. The choice of site will vary as their capacity and gate fees change, but haulage is a major factor so the waste management company will seek to avoid large travel distances. In this study, ultimate disposal sites were found to be within fifty miles of the WTS. In the case of recyclables these are generally not the place where the material is ultimately recycled, but the next link in a long chain of businesses involved in processing waste and returning it to the state of 'raw material', ready to be manufactured into a product with recycled content. This chain can extend to other parts of the UK, Europe, and for metals, some plastics, and some cardboard packaging, worldwide.

Reflection

An empirical observation from the case studies is that people discard perfectly good but surplus goods. Evidently it is not unthinkable to reclassify a product as a waste; expedience seems to overrule normal sense and prudence. The linear economy appears to reconstitute inside people's minds as a valve-like mechanism: allowing them readily to imagine goods as waste (under the pressure of getting a project completed, or when clearing out the loft), but much less to reimagine waste as goods – though some people do. In some circumstances the legal classification appears to hamper recovery, although in others it is ignored. The negative connotations of the term 'waste' may contribute, along with actual hazardousness and dirtiness in some instances, to a socially constructed notion of materials that are untouchable and unusable. Defence mechanisms against 'dirt' (Douglas, 2002) may be associated with any waste, whether useful or harmful. 'If we shun dirt, it is not because of craven fear, still less dread of holy terror. Nor do our ideas about disease account for the range of our behaviour in cleaning or avoiding dirt. Dirt offends against order' (Douglas, 2002: 2-3).

R. Pilot production of cross-laminated secondary timber and by-products

Figure 67 illustrates the stages of production of CLST undertaken by the author for the Crisp Street Exchange (CSE) live case study. The table is in use at the Crisp Street Exchange co-working space.

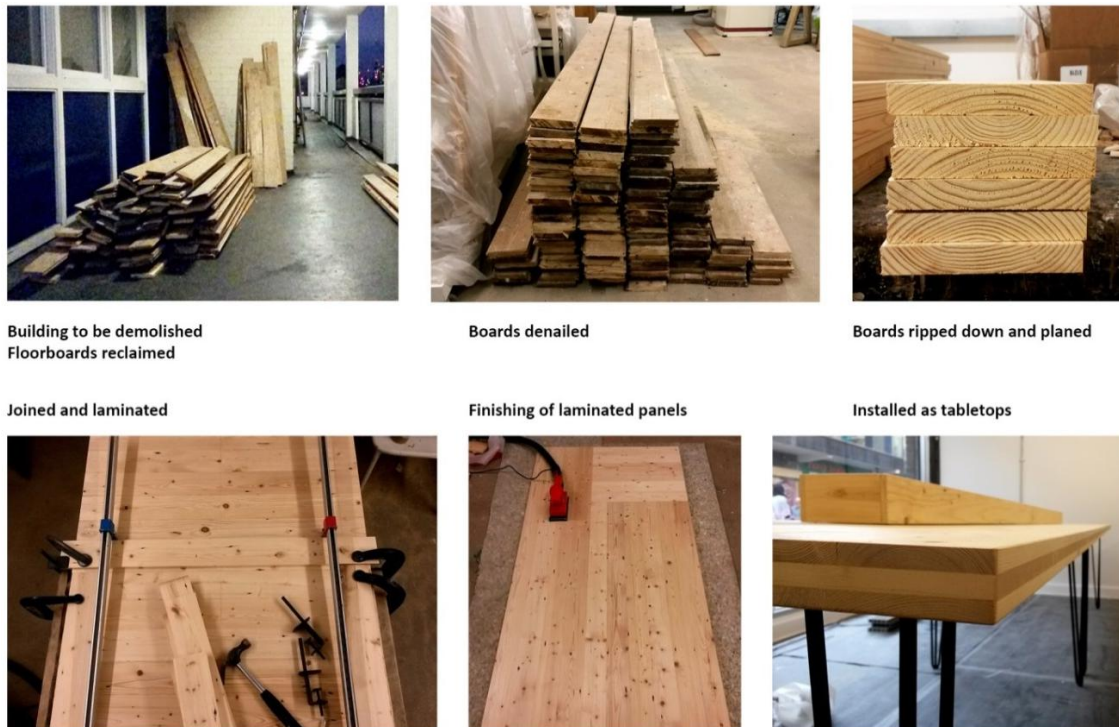


Figure 67: Photographs of the stages of production of CLST from reclaimed floorboards

In industrial-scale production of CLST, there would be various solid timber components that are not suitable for the main production line, for which alternative uses could be sought. One example is the framing elements of window sashes. Figure 68 illustrates a potential by-product of CLST production using sliding sash frames to make a cladding panel. There could also be high-margin, small-scale products like furniture and light fittings, which draw value from residual aesthetic qualities (e.g., of timber that has been subject to heavy weathering), rather than residual structural performance.



Figure 68: Sliding sash framing elements repurposed as cladding panels – two sides of two samples

S. Estimated quantities of timber emerging from UK building stock

Estimates of total UK wood waste and the quantity of wood waste generated by the construction industry have ranged widely, but from 2007 onwards the figures become more consistent (Table 31). The 2015 report by Veolia and Imperial College London (Voulvoulis, 2015) is excluded from calculation of averages as it has no explanation of its method or justification of its outlying figure. The average percentages suggest that C&D wood waste makes up something in the region of half of total wood waste; and of C&D wood waste, around half originates from demolition of the existing building stock. Waste generation is sensitive to changes in the strength of the economy, but according to the Tolvik report (2011), UK wood waste arisings are likely to fluctuate around 4.3 Mtpa. As a per capita figure, this is broadly aligned with that of Germany and the Netherlands (Tolvik, 2011).

Table 31: Estimated quantities of UK wood waste; blanks indicate no data available.

Year of data	UK total wood waste (Mtpa)	UK C&D wood waste (Mtpa; percentage of total)	Demolition only (Mtpa; percentage of C&D)	Method and source
	7.4	3.3 (45%)		Unreferenced citation of 'BRE/Hurley, 2004' (Defra, 2012c)
2003-04	10.6	5.0 (47%)	4.1 (82%)	Best estimates for C&D based on average of several other studies, overall wastes arisings data and estimates for the proportion by weight which was wood (Nikitas et al., 2005)
2005	7.5	2.9 (39%)		Review of previous surveys (Defra, 2012c; Fisher et al., 2006)
2007	4.5	1.9 (42%)	0.8 (42%)	Bottom-up analysis (interviews with producers/consumers) (Pöyry, 2009)
2007	4.6	2.3 (50%)	1.1 (48%)	Top-down analysis (information from trade and public bodies) (Pöyry, 2009)
2007	5.1	2.3 (45%)	1.1 (48%)	Revision of Pöyry (2009) with increased estimate of municipal solid waste (Tolvik, 2011)
2010	5.6	1.8 (32%)		WRAP surveys; unreferenced citation of 'AEA report, 2012' (Defra, 2012c, 2012d)
2010	4.3	2.0 (47%)	1.1 (55%)	Unspecified top-down analysis (Tolvik, 2011)
2010	4.1	2.1 (53%)	1.1 (52%)	Top-down based on a waste factor applied to consumption volumes (WRAP, 2011)
2015	10.0			Unspecified (Voulvoulis, 2015)
Average 2003-10	6.0	2.6 (44%)	1.6 (61%)	Excludes Voulvoulis (2015)
Average 2007-10	4.7	2.1 (45%)	1.0 (48%)	Excludes Voulvoulis (2015)

T. Basis for calculating numbers of dwellings that could be made from CLST

Table 22 in section 6.2.3 and the commentary in section 6.4.2 draw on estimates of the total quantity of solid secondary timber that could be used in CLST and the number of dwellings that this volume of CLST could build. This appendix states the assumptions made and provides the working that led to those figures.

Based on Table 31 in Appendix S, it appears that around 1 Mtpa of timber is removed from the building stock.

If the timber intensity of 3.7 tonnes per capita for housing in the London Borough of Tower Hamlets (Romero et al., 2019; Appendix B) is taken as representative of buildings in the UK (a bold assumption, but the best measure available), then the UK building stock contains about 240 Mt of timber. If 1 Mtpa emerges as waste, then the rate of removal is 0.42%. This is above most estimated demolition rates for housing (van der Flier and Thomsen, 2006) but below the rate for non-residential demolition (Hradil et al., 2014), and proximate enough to lend credibility to the estimate of timber waste arising.

The total potential UK feedstock may then be estimated by multiplying the estimated total demolition wood waste by the average proportion found to be solid wood (0.72 in Pöyry, 2009; 0.56 in WRAP, 2011; average 0.64), giving 0.64 Mtpa.

Some of this solid wood will be from elements that were never strength graded – the suitability of which will depend on actual mechanical properties and options for use within a CLST section that require further investigation – or from elements like windows and doors that do not lend themselves to simple recovery of rectangular sections. In the absence of actual data, a factor of 0.5 is assumed here to account for solid wood that cannot feasibly be used in CLST, leaving 0.32 Mtpa suitable secondary solid timber to be targeted for use in CLST.

This is only counting demolition waste. It is likely that a proportion of construction waste is also accessible (depending on how the material is sourced) and useable. Construction waste has been disregarded in these calculations because it cannot be foreseen like demolition waste. If construction waste were included, the volume of timber potentially available to the CLST enterprise may be as much as doubled.

To establish the number of dwellings that could be produced from this quantity of feedstock, the Waugh Thistleton scheme Dalston Works¹⁴ is taken as a precedent. This uses 3,852 m³ of CLT¹⁵ and was reported to provide 15,960 m² floor area (78% residential, 22% commercial).¹⁶ If the CLT providing residential space is proportional to the whole development then 78% of 3,852

¹⁴ www.waughthistleton.com/dalston-works, accessed 3rd September 2018

¹⁵ <http://www.ramboll.co.uk/projects/ruk/dalston-lane>, accessed 3rd September 2018

¹⁶ www.waughthistleton.com/project/dalston-lane, accessed 12th March 2016

$\text{m}^3 = 3,004 \text{ m}^3$. This delivered 121 dwellings, i.e., 24.8 m^3 per dwelling. Density of CLT is in the region of $371\text{--}445 \text{ kg/m}^3$ (Stora Enso, 2014) an average of which is 408 kg/m^3 . Therefore CLT mass per dwelling is assumed to be 10,000 kg.

In the notional situation of all 0.32 Mtpa suitable secondary solid timber reaching a CLST plant, if an end yield of 60% is assumed (see section 6.4.2) and 10 t is needed for each dwelling (i.e., CLST made entirely from secondary timber), then each year the structural material for around 20,000 dwellings could be made from timber that is currently discarded. More realistically, given competition from existing timber waste management, if it is assumed that 35% of total suitable timber reaches CLST plants and yield is 60%, then the structural material for around 7,000 dwellings could be made each year.

Looking at a single metropolitan area to assess the quantity of secondary timber that could plausibly be harvested by a single CLST enterprise, Pöyry (2009) found that London's timber demolition waste amounted to about 14% of total UK timber demolition waste. A CLST factory processing all of the suitable secondary solid timber in London could produce the structural components for a maximum of 2,800 dwellings per year. If 35% is harvested, London's secondary timber could produce 1,000 dwellings per year.

According to Pöyry (2009), quantities of timber demolition waste that are comparable to London's also arise in the southeast of England (17% of total UK demolition waste), eastern England (12%) and the northwest of England (10%), although less urbanised regions would imply greater haulage distances. Disregarding the rest of the UK, these three regions in addition to London could produce the structure for up to 10,000 dwellings per year if all suitable timber is harvested; or applying the harvest rate of 35%, for 3,700 dwellings: 1,200 in the southeast, 800 in the east and 700 in the northwest.¹⁷ Given that Swan Housing have invested in a factory to assemble CLT modular homes that is expected to deliver 300–400 per year,¹⁸ these CLST opportunities would appear to be worthy of further investigation.

¹⁷ This leads to a total of 37,000 tpa timber ending up in CLST, or 5.8% of the total 0.64 Mtpa solid secondary timber from demolition in the UK.

¹⁸ <https://www.swan.org.uk/home/news/swan-delivers-the-first-of-their-modular-homes-to-site-in-basildon.aspx>

U. Notes on life cycle assessment in relation to cross-laminated secondary timber

The envisaged Master's project on LCA of CLST comprised two parts: a comparison of CLPT and CLST production and a comparison of various waste management or component management options for waste wood. Carrying out an LCA thoroughly is very time consuming. Only the first part of the envisaged project was completed (Zou, 2017; Appendix I-6). The second part would have adopted a method similar to that of Zink et al. (2014) in their comparison of repurposing versus refurbishment of a smartphone. The functional unit would be a quantity of secondary timber, and the assessment would use consequential LCA (Ekvall and Weidema, 2004) to compare its use in CLST to recycling into particleboard, recycling into animal bedding, energy recovery and landfill. Below, this appendix presents further material from Zou's (2017a) study, but first this is placed into context in a reflection on the use of LCA for timber.

Morris (2017) uses LCA to decide between 'recycling, burying or burning' secondary timber. He sets out a 100 year assessment period for an assessment of waste management options for timber, but does not take into account the potential for multiple life cycles, which is critical to timber cascading (e.g., energy recovery is always an option after possibilities for material use have been exhausted; Dadoo et al., 2014; Fraanje, 1997; Hekkert, 2000; Höglmeier et al., 2013; Sathre and Gustavsson, 2006; Sirkin and ten Houten, 1994; Stahel, 1982). Morris's approach implies that all wood waste – a very broad category of components – should be subject to a single 'optimal' approach. He does not consider the outputs of recycling, burying or burning as options that should have their subsequent life cycles (or lack of) assessed, but as final outcomes to be compared; as a result he ignores subsequent potential uses. This leads to perverse conclusions such as, 'under one of the alternative methods, wood substitution for coal boiler fuel and landfill options with high methane capture efficiency are the best for the overall score; recycling options are next to the worst' (Morris, 2017).

The potential for multiple cascading uses of timber means it is important to think about the extent to which decisions taken now influence what is possible in future. Recycling to make animal bedding and energy recovery are single use activities that do not result in a recoverable material. Recycling solid timber to make particleboard precludes (at least at present) anything except energy recovery at the end of the next use phase. If a recycling process does not imperil the ability to recover energy from timber, an LCA comparing recycling to energy recovery can ignore the effect of the energy recovery, as it is present in both options (notwithstanding potential differences in quantities). The assessment then becomes a question of whether the net impacts of the recycling process are positive or negative; i.e., is recycling preferable to not recycling? The reasons why recycling could be worse than not recycling include transporting materials to a distant processing plant (it is worth noting that it may not be possible to reach a

definitive answer: if recycling produces positive impacts in some categories and negative in others, a value judgements would need to be made about which impact category is of most importance). Likewise, as long as an upcycling (or reuse or repurposing) process retains the ability to recycle and then recover energy in future, any extended use of components will be preferable to recycling, and to energy recovery, as long as upcycling is better than not upcycling.

This author leans towards a position of optimism on the use of timber, by assuming that the performance it provides usually means that doing something with it is preferable to doing nothing. This is a common sense assumption based on seeing timber performing useful duties in industry, i.e., duties that would otherwise need to be undertaken by another material. To look at it from the other perspective, if all treatments of secondary timber were to have net negative impact, then timber would be seen as a menace, like residual household waste. Processes that retain the material for future cycles of use would then be undesirable. The preferred route would be to incinerate immediately, and thus avoid building up multiple cycles of negative impact. Circumstances can be imagined in which this would be the case: remote locations far from recycling plants and without local demand for timber but with a pressing need for fuel, for instance. In cities with waste management infrastructure, instinct suggests that calculating net impacts of reuse and recycling processes would lend support to them as positive stages in the cascading use of timber. This thesis has suggested that, furthermore, improvement upon reuse and recycling may sometimes be possible through repurposing and upcycling.

LCA can provide a very detailed but partial view on decision making. To get a wider view of all the environmental effects of, for instance, choosing what to do with waste wood, there needs to be more robust assessment of net impacts at t_0 , accounting for both process impacts and avoided impacts, the rate of displacement, and in the case of biogenic materials' global warming potential, retained sequestered carbon. The assessment then needs to extend through time to account for expected periods of use, and best estimate of future uses and *their* net impacts at t_1 , t_2 , t_n . Arguably this involves so many assumptions that it becomes unwieldy, unreliable and open to manipulation. Nevertheless, the effect of *not* considering multiple life cycles is to reach conclusions like Morris (2017a): that the best option for timber can sometimes be to send to landfill and capture methane. Methane will still be available for capture after more productive uses of timber have been exploited.

Further limitations of LCA are the necessity to impose a system boundary to make calculations operable, and the fluidity of what might be displaced in consequential LCA. In an open system, a line must be drawn to define what will be assessed and knock-on effects that will be excluded (Bovea and Powell, 2016; Ekvall and Weidema, 2004). In consequential LCA of waste management options, the avoided impacts of displaced primary materials are credited to the assessed waste management option. A study could assess displacement of primary production of the same product (e.g., recycled wood becomes particleboard for a kitchen worktop; primary wood for equivalent particleboard worktop is displaced). However, sometimes the secondary

particleboard would not replace primary particleboard, but would replace stone, Corian, hardwood or stainless steel. The impacts of a melamine finish would need to be added to make the particleboard functionally equivalent. Similarly, CLST could be assumed to replace CLPT, but very different outcomes would be found if the study assumed instead that it displaces structural steel, concrete or brick. There would also be a multitude of knock-on effects that should be included within the system boundary of a thorough LCA of CLST assumed to displace, say, steel, such as different needs for fire separation, fire protection, insulation and building envelope. If the specific alternative material that is to be displaced is known, then its specific impacts can be used in the LCA. If it is not, then, like energy mix calculations, the 'typical' alternative should be modelled, e.g., by considering what proportion of kitchen worktops are made of stone, Corian, hardwood, particleboard and so on.

Although all of these issues mean that an LCA of sufficient thoroughness could entail years of work, and results should be interpreted and used with considerable wariness, the view remains that the assessor should simply be clear and open about what has and has not been taken into account. Despite drawbacks it appears to be the best method available, where the quantification of impacts is considered necessary. What follows are the systems boundary diagrams for CLPT (Figure 69) and CLST (Figure 70) used in Zou's (2017a) LCA, and the midpoint results for cradle-to-gate and cradle-to-site assessments (Figure 71).

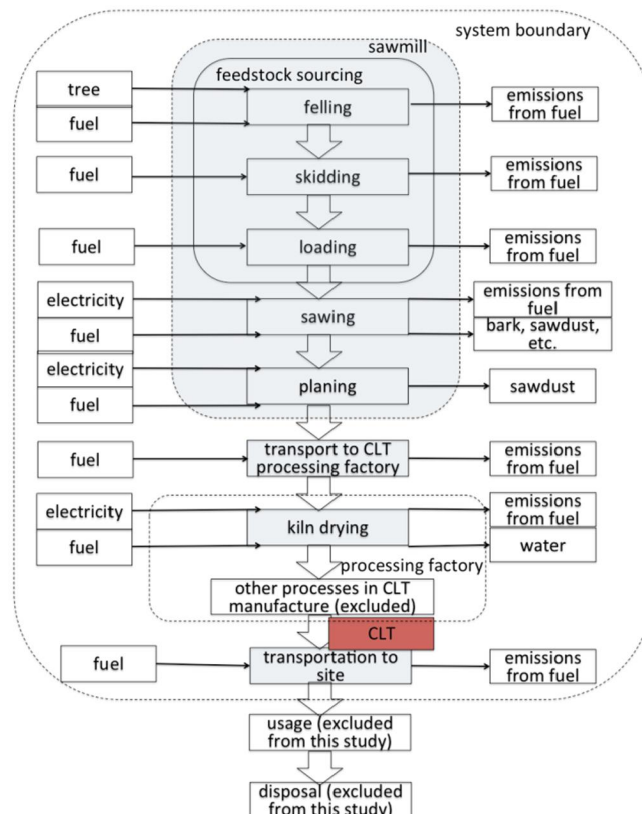


Figure 69: The system boundary of the process of CLPT showing inputs and outputs

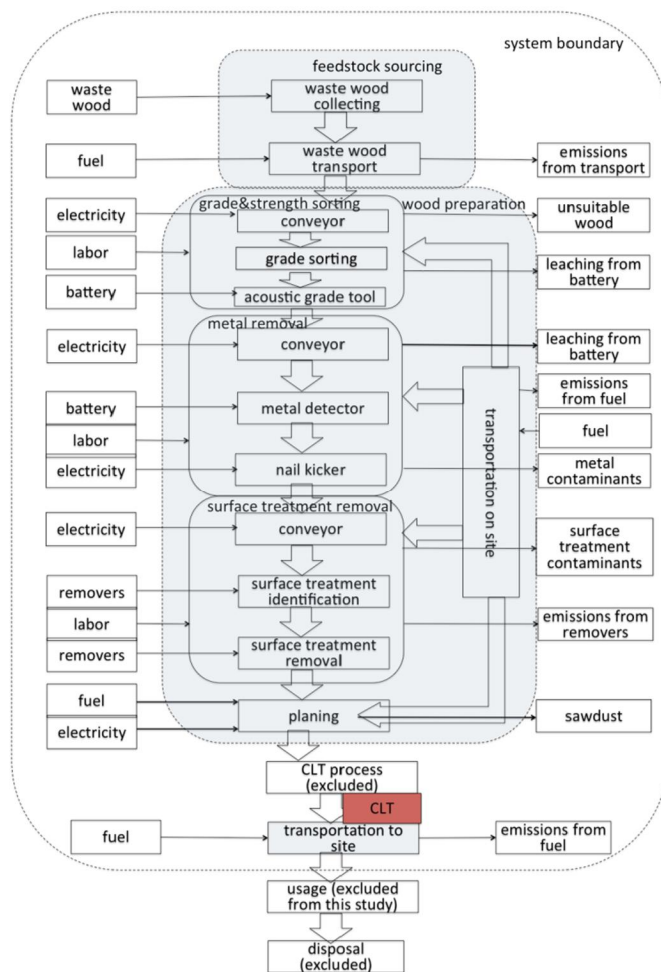


Figure 70: The system boundary of the process of CLST showing inputs and outputs

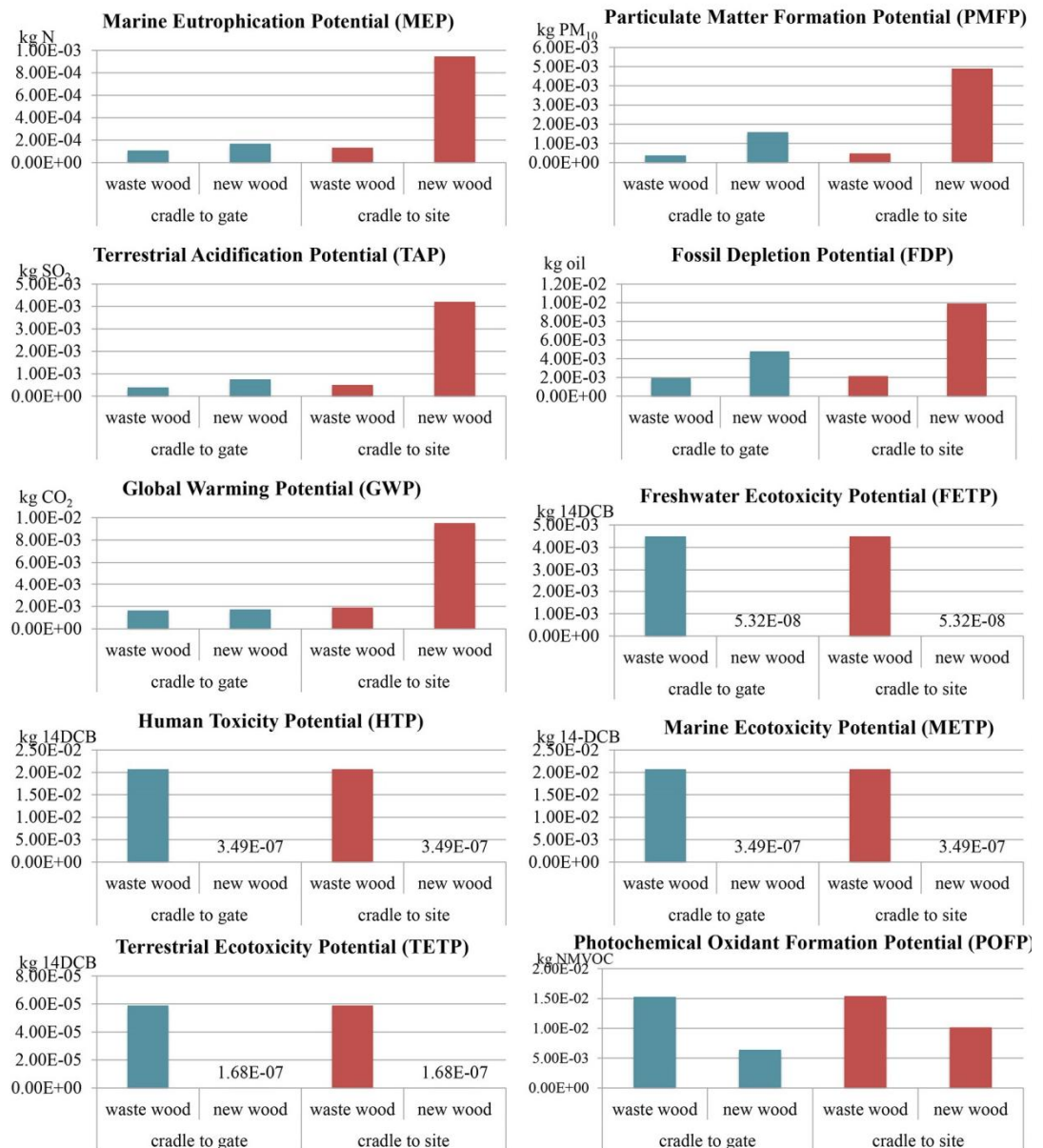


Figure 71: Life cycle impact assessment – midpoint scores for CLST and CLPT for cradle-to-gate and cradle-to-site assessments

V. Notes on the genesis and novelty of cross-laminated secondary timber

The researcher first proposed the use of secondary timber in CLT in December 2014, after carrying out the initial case study research and reading a UCL colleague's Master's thesis on the adoption of CLT in the UK (Jones, 2014). Initial scoping work led to the instigation of two Master's dissertation projects to test the mechanical properties of CLST and CLPT in April 2015, later published as part of Rose et al. (2018). The preliminary work was first presented at the UCL Centre for Urban Sustainability and Resilience *Research Showcase* event in November 2015 (Rose et al., 2015b). Sample panels were displayed at The Great Recovery's stand at Ecobuild, London, in March 2016. Pilot production of two larger CLST panels was carried out in March-April 2016 and installed as a 'banqueting table' at Chrisp Street Exchange in May 2016 (see section 5.4.3). The research was presented publicly at the Victoria & Albert Museum *Friday Late* in July 2016, then as part of an EU COST Action academic workshop in August 2016 (Rose and Stegemann, 2016) and at an academic workshop convened by TU Munich in March 2017 (Rose and Stegemann, 2017). During this period three further MSc dissertation projects and an MRes research project were instigated in connection with CLST.

An ongoing review was begun in January 2015 to investigate whether the concept of using secondary timber in CLT had already been carried out in practice or investigated by other researchers. Correspondence with figures from leading CLT and glulam manufacturers and suppliers (Stora Enso, KLH, Eurban and InWood) suggested that none are producing or considering production of CLST: factories are typically located in heavily forested parts of Austria, Germany etc., where there is little post-consumer waste wood; they are set up around the availability of huge quantities of primary timber; the idea of using secondary timber is completely alien to their context. A peer reviewer of Rose et al. (2018) noted that, 'discussion of CLST (if we are to call it that) is not really present in the wider literature (even if it has been discussed within the timber engineering community).'

Although European Standard BS EN 16351:2015 (BSI, 2015) does not allow used wood in CLT as a precaution, and no manufacturers presently appear to be considering CLST, occasional suggestions to use secondary timber in engineered wood products were found in the academic literature. Geldermans (2009) made passing reference to cascading use of timber: 'virgin beam - reused beam - floor joist - planks - laminated board - chipboard - paper - compost'. Similarly, Sakaguchi (2014) suggested that lamination in a glue laminated product could be a stage in timber's cascading use. Neither study conceived the product as CLT, or moreover recognised its greater potential performance and lifespan than other products in the cascade, but rather saw it as another drop in 'quality'. Neither author appears to have pursued the idea beyond passing reference. As noted in section 6.3.1 of this thesis, researchers at the University of Utah with industry partners investigated the manufacture of interlocking 'ICLT' without adhesives or fasteners (Smith, 2011). Their work considered sourcing the timber from existing buildings, but they chose instead to explore pilot manufacture and mechanical testing of ICLT using the larger

quantities of standing trees affected by pine bark beetle in their region (Wilson, 2012). This context is relatively sparsely populated and more forested than dense urban areas in Europe, where secondary timber is far more plentiful.

Assessing the potential of mass timber construction to replace concrete and steel in Australia, Kremer and Symmons (2015) recommended that with government support, greater demand for CLT and other mass timber products could benefit local forestry industries as well as providing a market for wood emerging from demolition:

The reclamation of lower grade material and opportunity to recycle timber from demolition and other wastage sources for the production of CLT production provides both financial and political advantage in an increasingly carbon-constrained world. These factors might open the door to government assistance to establish a local industry if doing so aids the nation's commitments to reduce overall carbon footprints through sequestration and a reduced reliance on more energy-intensive processes involved in the production of steel and concrete. (Kremer and Symmons, 2015)

Lastly, in a study of timber deconstruction and reuse practices in the USA and the UK, one of the conclusions reached by Bergsagel (2016) was that the 'increased variability in mechanical properties [of secondary timber] is appropriate for laminated engineered wood products'. He recommended that 'research should be conducted on the material efficiency of producing laminated engineered wood products from a more variable reclaimed timber feedstock. This could be for the whole section, or only for the central laminations, which provide depth and mass to a section without being subject to the same stress grade requirements'.

From the review, it is concluded that researchers have outlined concepts similar to CLST, but on no occasion has this been developed through detailed investigation of the idea's feasibility or any form of testing. No practical implementation of CLST is currently taking place by industry incumbents. The author's pilot production of CLST for Chrisp Street Exchange is thought to be a world first of its kind.

S1. ABAQUS model geometry

S1.1. Compression on the Y-axis

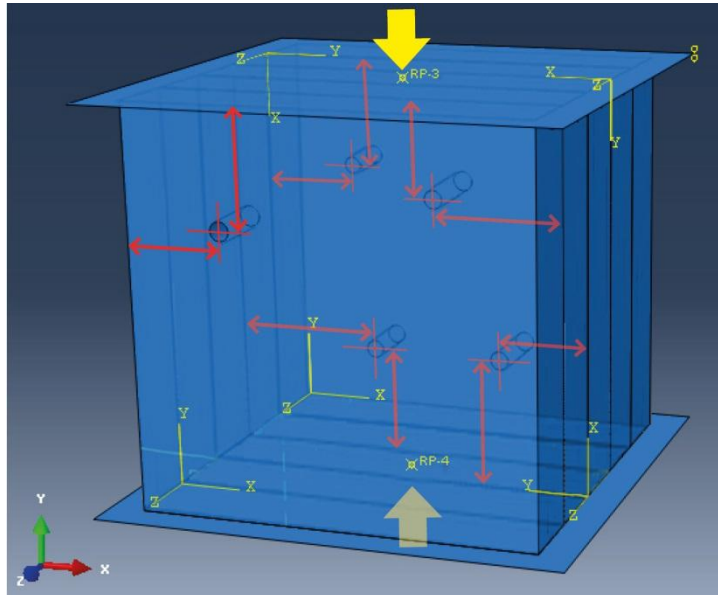


Figure 72. Compression specimen; lamella dimensions – Length = 85 mm; Width = 85 mm; Thickness = 17 mm; defect dimensions off sides (as Table 2 column 4) shown in red line, rotated 90° for each lamella to avoid their coincidence, i.e., are measured from the following sides: front lamella – LHS and top; second lamella – top and RHS; third lamella – RHS and bottom; fourth lamella – bottom and LHS; rear lamella – LHS and top.

S1.2. Out-of-plane bending of the panel's X-axis around the Y-axis

Run Q: Single large hole located at centre of span

Single large central hole in outer lamellae; hole properties – diameter = 15 mm centred at 410 mm and 25.5 mm from the outer edges, oriented in the panel's Z-axis.

Run R: Single large hole located off-centre of span

Single large shifted hole in both outer lamella; hole properties – diameter = 15 mm centred at 300 mm and 25.5 mm from the outer edges, oriented in the panel's Z-axis.

Run S: Miscellaneous spread out holes in all lamellae

Spread of holes as Table 32 and Table 33, oriented in the panel's Z-axis.

Table 32. Defect table: bottom lamella (all dimensions in mm).

Diameter	4	10	2.8	6	11	4
Thickness	HB, IF	T	T	HB, IF	T	HB, OF
X_centre	40	250	400	440	620	670
Y_centre	21	25	30	31	11	21

X_centre, Y_centre from LHS edge

T=Through thickness of lamella; HB= half-blind (hole only going through half the lamella thickness)

IF=Inner Face (stuck to middle lamella) ; OF=Outer Face (external to whole assembly)

Table 33. Defect table: middle lamella (all dimensions in mm)

Diameter	4	6	6	4	10	4
Thickness	HB, BF	T	T	HB, FF	T	HB, FF
X_centre	150	200	380	420	570	780
Y_centre	30	40	20	21	26	30

BF: Back face, FF: Front face

Top lamella: same as bottom lamella but rotated around Y_axis by 180°.

Run T: Miscellaneous holes centrally clustered in all lamellae

Spread of holes as Table 34 and Table 35, oriented in the panel's Z-axis.

Table 34. Defect table: bottom lamella (all dimensions in mm).

Diameter	4	6	10	4	4	6
Thickness	HB, IF	T	T	HB, IF	HB, OF	T
X_centre	300	350	370	400	420	440
Y_centre	21	11	30	25	21	31

X_centre, Y_centre from LHS edge

T=Through thickness of lamella; HB= half-blind (hole only going through half the lamella thickness) IF=Inner Face (stuck to middle lamella) ; OF=Outer Face (external to whole assembly)

Table 35. Middle lamella (all dimensions in mm).

Diameter	6	4	6	10	4	4
Thickness	T	HB, BF	T	T	HB, FF	HB, FF
X_centre	300	350	380	410	450	500
Y_centre	40	30	20	26	20	30

BF: Back face, FF: Front face

Top lamella: same as bottom lamella but rotated around Y_axis by 180°.

Glossary of terms

Abduction – sometimes used interchangeably with the term ‘retroduction’; and sometimes used to mean formation of hypotheses, with retroduction as the process of testing and refining hypotheses and final selection. In this thesis, abduction is used as the overarching descriptive term for both aspects.

Building component / component – an object made up of one or more materials, formed in a way to meet a specific purpose in construction.

Carbon emissions – used for brevity, but unless otherwise stated refers to CO₂e emissions.

CEN/TC 350 – European standards that bring into being the standards for assessment of environmental performance of buildings and building products, BS EN 15643, BS EN 15804 and BS EN 15978.

Circular economy – an economy that is restorative and regenerative by design (Ellen MacArthur Foundation, 2015). Actual ‘circularity’ is unattainable (Cullen, 2017); in the thesis the term ‘circular economy’ is used for convenience and familiarity, but with the proviso that what is really meant is an economy in which traits of circularity are more developed than at present, or there is more emphasis on inner circle use of materials than at present.

Construction industry – those industries which directly contribute to the creation and maintenance of the built environment; and whose activities are directly related to the creation and maintenance of the built environment (where the ‘built environment’ includes all the physical infrastructure put in place by the building and construction industries; Smith et al., 2002).

Cross-laminated timber – a structural, prefabricated building component formed of layers of timber laminated at right angles to one another, making panels that can be used for walls, floors and roofs.

Deconstruction – careful dismantling of a building or part of a building so that its constituent elements can be reused.

Demolition – typical method of removing an unwanted building or part of building using destructive techniques.

Direct reuse – as defined by the WFD, reuse of a component after only minor ‘checking, cleaning or repairing recovery operations’ – as opposed to ‘reuse’ of a repurposed or upcycled product.

Downcycling – a process that transforms secondary materials, such that the resulting product has the potential to perform a duty normally performed by a material of lesser environmental

impacts, i.e., that reduces performance. Usually a destructive process that returns components to raw materials.

Duty – used in this thesis in relation to building component performance (see below).

Environmental Product Declaration (EPD) – under CEN/TC 350 (BS EN 15804), a means for manufacturers to demonstrate products' environmental credentials using LCA.

Material recovery – a general term, of which preparing for reuse and recycling are special cases. It includes backfilling and other forms of material recovery such as road construction, but excludes energy recovery (European Commission, 2018).

Performance – used in this thesis to mean a building component's capacity to perform a duty (that would otherwise be performed by a material it displaces) over a period of time. A secondary component that can displace a primary product with high environmental impacts can be said to achieve high performance.

Repurposing – reusing a component for a purpose different to that for which it was originally intended.

Superuse scout – a new profession proposed by van Hinte et al. (2007), that recognises components that have the potential to be useful, understands transportation and costs and possible methods to make secondary components suitable for new uses.

System – a cohesive set of natural or human-made interacting elements (Bertalanffy, 1968); 'systems thinking is only an epistemology, a particular way of describing the world. It does not tell us what the world *is*. Hence, strictly speaking, we should never say of something in the world: "It is a system", only: "It may be described as a system". (Of course, keeping to that rule is tedious!)' (Checkland, 1983).

Upcycling – a process that transforms secondary materials, such that the resulting product has the potential to perform a duty normally performed by a material of greater environmental impacts, i.e., that increases performance. Usually a non-destructive process that avoids returning components to raw materials and instead capitalises on their existing attributes.